Eesti Maaülikool
Estonian University of Life Sciences

CHARACTERISTICS OF BIOETHANOL FUEL OBTAINED FROM LIGNOCELLULOSE BIOMASS IN INTERNAL COMBUSTION RECIPROCATING ENGINES WITH SPARK- AND COMPRESSION-IGNITION

LIGNOTSELLULOOSSEST BIOMASSIST SAADAVATE BIOETANOOLKÜTUSTE KARAKTERISTIKUD SÄDE- JA SURVESÜÜTEGA SISEPÕLEMISMOOTORITES

ARNE KÜÜT

A Thesis
for applying for the degree of Doctor of Philosophy
in Agricultural Engineering

Väitekiri
Filosoofiadoktori kraadi taotlemiseks põllumajandustehnika erialal

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Opponents: Prof Gints Birzietis, Dr. Sc.
Motor Vehicle Institute
Latvia University of Agriculture

Researcher Hannu Mikkola PhD
Department of Agricultural Sciences
University of Helsinki

Supervisor: Prof. Jüri Olt, Dr. Sc.(Eng)
Institute of Technology
Estonian University of Life Sciences

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CONTENTS

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III. Küüt, A.; Ilves, R.; Mikita, V.; Olt, J. (2012). The characteristics of bioethanol fuel in internel combustion engines with compression-ignition. 40th International symposium "Actual Tasks on Agricultural Engineering, Opatija, 21–24.02.2012., 117–125.

IV. Küüt, A.; Ritslaid, K.; Olt, J (2011). Study of potential uses for farmstead ethanol as motor fuel. Agronomy Research, 9 (1), 125–134.

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VI. Olt, J.; Mikita, V.; Ilves, R.; Küüt, A. (2011). Ethanol as an additive fuel for diesel engines. 10th International Scientific Conference "Engineering for Rural Development", 26–27 May, 2011, Jelgava, Latvia University of Agriculture, 2011, 248–253.

VII. Ritslaid, K.; Küüt, A.; Olt, J. (2010). State of the Art in Bioethanol Production. Agronomy Research, 8(1), 236–254.

VIII. Küüt, A.; Olt, J. (2010). Use of bioethanol fuel as regular fuel (291–298). Actual Tasks on Agricultural Ebgineering. Opatija. Zagreb: HINUS.

The contribution of the author to the papers

Paper	Study design	Data collection	Data processing	Manuscript preparation
I	**AK,** JO, OP	**AK,** JO	**AK**, OP, JO	**AK**, JO, OP
II	RI, **AK**, JO, VM	**AK**, JO, RI	RI, **AK**	RI, **AK**, JO, VM
III	JO, **AK**, RI, VM	VM, **AK**, RI	**AK**	**AK**, JO, RI, VM
IV	**AK**, KR, JO	**AK**, KR	**AK**, JO, KR	**AK**, KR, JO
V	**AK**, RI, JO, VM	RI, **AK**, MM	RI, **AK**	**AK**, RI, JO, VM
VI	JO, VM, RI, **AK**	JO, VM, RI, **AK**	JO, VM, RI, **AK**	JO, VM, RI, **AK**
VI	KR, **AK**, JO	KR, **AK**, JO	KR, **AK**, JO	**AK**, KR, JO
VII	KR, **AK** JO	KR, **AK**, JO	KR, **AK**, JO	**AK**, KR, JO
VIII	**AK**, JO	**AK**, JO	**AK**	**AK**, JO

AK – Arne Küüt; JO – Jüri Olt; KR – Kaie Ritslaid; MM – Marten Madissoo; OP – Olga Panova; RI – Risto Ilves; VM – Villu Mikita.

INTELLECTUAL PROPERTY

Titel:	Formation method of fuel-air mixture of reciprocating engine and flexible-fuel system
Patent number:	EE 05665 B1
Filing date of the application:	17.03.2011
Priority date:	17.03.2013
Publication date:	17.06.2013
Inventor name:	Olt, J., Küüt, A., Ilves, R.

The contribution of the author to the patent

Study design	Preparation and elaboration activities	Study of prior art	Application preparation
RI, JO, **AK**	**AK**, RI, JO	**AK**, JO, RI	JO, RI, **AK**

AK – Arne Küüt; JO – Jüri Olt; RI – Risto Ilves.

ABBREVIATIONS AND SYMBOLS

Abbreviations

CAD	Computer-Aided Design
CEN	European Committee for Standardization
CNC	Computer Numerical Control
DIN	Deutsches Institut für Normung (in Germany)
DLGE	Diluted Low Grade Ethanol
DVPE	Dry Vapour Pressure Equivalent
EBK	Estonian Bioethanol Cluster
ECU	Engine Control Unit
EREC	European Renewable Energy Council
ETBE	Ethyl Tert-Butyl Ether
FFV	Flexi Fuel Vehicles
FNR	Fachagentur Nachwachsende Rohstoff e. V. (in Germany)
IEA	International Energy Agency
IFOS	Institut für Oberflächen- und Schichtananalytik GmbH (in German)
ILUC	Indirect Land Use Change (EU memo)
LGBE	Low Grade Bio Ethanol
LGBE-III	Low Grade Bio Ethanol 3-d fraction
LGE	Low Grade Ethanol
MBT	Maximum Brake Torque
MTBE	Methyl Tert-Butyl Ether
NO_X	Nitros Oxides
rpm	Revolutions Per Minute
SAE	Society of Automotive Engineers
TDC	Top Dead Center
TN	Total Nitrogen
TS	Total Solids
ICE	Internal Combustion Engine
VS	Volatile Solids

Symbols

Latin

a_c	ethanol content, vol %
B_a	air consumption, kg h^{-1}
b_e	specific fuel consumption, kg kWh^{-1}

B_f	fuel consumption, kg h^{-1}
B_{fc}	petrol fuel consumption, kg h^{-1}
B_{fd}	diesel fuel consumption, kg h^{-1}
B_{fet}	ethanol fuel consumption, kg h^{-1}
$B_{f.en}$	fuel consumption of high pressure pump during engine testing, g min^{-1}
$B_{f.fp}$	fuel consumption of high pressure pump, g min^{-1}
C_F	expenses on field area, € ha^{-1}
C_f	fuel cost, € h^{-1}
c_f	fuel price, € kg^{-1}
C_{fbio}	cost of bio-fuel, € h^{-1}
C_{fc}	cost of petrol, € h^{1}
c_{fc}	price of petrol, € kg^{-1}
C_{fd}	cost of diesel fuel, € h^{-1}
c_{fd}	price of diesel fuel, € kg^{-1}
C_{fet}	cost of ethanol, € h^{-1}
c_{fet}	price of ethanol, € kg^{-1}
C_{freg}	cost of regular fuel, € h^{-1}
c_w	wages, €
i	number of cylinders
i_l	number of sections of fuel-injection pump
k_U	coefficient of metrol source
k_a	coefficient of absorption
k	factor which takes into account the reduction in the value of pump fuel delivery depending on engine test mode
m_f	fuel amount, kg
m_{fc}	mass of fuel for one cycle, kg
n	number of measurements
n_c	total number of cycles

n_{cam}	camshaft rotational speed of fuel-injection pump, rpm
n_e	number of crankshaft revolution per minit, rev min^{-1}
P_h	driving power of the tractor, kW
P_i	indicated power, kW
P_e	engine power, kW
P_m	mechanical power loss, kW
p_m	mean mechanical loss pressure, kPa
p_{me}	mean effective pressure, kPa
p_{mi}	mean indicated pressure, kPa
p_z	pressure of combustion process, kPa
$SD_{\max}$	system deviation, torque
t_e	pretreatment temperature, °C
t_h	hydrolysis temperature, °C
T_e	engine torque, Nm
T_c	resistance moment
U	cumulative uncertainty
u_A	metrol type A
u_B	metrol type B
U_e	extended uncertainty
$V_{f.en}$	pump fuel delivery during engine testing, cm^3 per cycle
$V_{f.fp}$	pump fuel delivery, cm^3 per cycle
V_i	capacity of section *i*, cm^3 min^{-1}
v_p	working speed of the agricultural vehicle
Q_{HV}	heating value, kJ kg^{-1}
W	work of one cycle, kJ

Greek

α_i	ignition timing advance
Δp	change in the final pressure of combustion process
Δc_f	relation of bioethanol production and actual price
ΔC_f	relation of bioethanol cost
η_c	combustion efficiency, %
η_e	engine efficiency, %
η_i	indicated engine efficiency, %
η_f	fuel conversion efficiency, %
η_t	thermal efficiency, %
η_T	driving efficiency of the tractor, %
ξ	nominal driving force efficiency of the tractor,%
ρ_f	fuel density, g $(cm^3)^{-1}$
τ_d	test duration, h
τ_t	number of strokes

INTRODUCTION

The energy crisis and climate warming have given rise to the search for alternative fuels. The main reason for the energy crisis is the limited amount of fossil fuels. According to a report by the World Energy Council, about 82% of the world's energy needs are currently covered by fossil resources such as petroleum, natural gas and coal (Soetaert W. et al., 2009). It has been agreed that at the current consumption rate the petroleum resources will be depleted "in 50 years, natural gas in 65 years and coal in about 200 years" (Vandamme et al., 2004). However, the scientists from UC Davis claim on the basis of petroleum markets' expectations that petroleum may become depleted 90 years before the availability of technologies which replace petroleum. According to Debbie Niemeier, one of the participants of the study, scientists have proven that the development of renewable energy's production for the energy market will take longer than expected as the total energy consumption is increasing. Niemeier warns that their study indicates the possibility that current goals related to renewable energy are not sufficient to prevent damage to the society, economic development and ecosystems. (Sutt, 2010)

Increasingly more attention is paid to biofuels which originate from renewable resources. Here the concept of renewable biofuel must be explained. Biofuels can be considered renewable if they are used within the limits of some territory's re-production (e.g. country) or less. Renewability is determined by the ratio between re-production and consumption, not the rate of growth (Muiste; Kask, 2000).
The most ambitious goal thus far in respect of the development and exploitation of renewable energy sources appears to be that articulated by the European Renewable Energy Council. According to the European Renewable Energy Council EREC (2010) in March 2007, the heads of states and governments of the 27 EU member states adopted a binding target of 20% renewable energy in final energy consumption by 2020 and 100% by 2050 (Adelekan, 2011).

As a member of the European Union, Estonia must fulfil its role in the development of renewable energy by meeting the requirements of the directive 2009/28/EC. The requirements stipulate that by the year 2012 the proportion of renewable energy must be 25% of end consumption and renewable energy based fuels must amount to 10% in transport.

Internal combustion engine fuel comprises a relatively high proportion of the energy need. Two globally known biorenewable transport fuels are currently available which may replace petroleum-based petrol and diesel. These are bioethanol and biodiesel (Demirbas, 2006). Currently the most widely used biorenewable engine fuel in the world is bioethanol. Biofuels amount to 0.5% of primary energy used in the world. The production of biofuels increased by 13.8% in the year 2010. The main contributors to the growth of ethanol production were North America, South America and Central America (BP Statistical Review of World Energy June 2011). Biofuel production in the Americas amounted to three quarters of the world's total production.

Ethanol has been used as an Otto engine fuel starting from the dawn of automotive industry. The first commercial vehicle which was capable of running on petrol, kerosene or ethanol was Ford T built in 1908. The decreasing prices of petrol and prohibition of alcohol consumption made ethanol an impractical fuel (Vares, 2008; Ford 2009).

In comparison with other biofuels (gaseous fuel, solid fuel), the advantages of using ethanol in internal combustion engines are its properties which are very similar to conventional fuels. As a result of this, the internal combustion engine requires less rebuilding or modification. It is known that the calorific value of ethanol is 69% of petrol, which causes higher specific fuel consumption. At the same time a higher octane number and a better anti-knock index considerably improve the performance figures of the engine, if the compression ratio is increased. Lower combustion temperature and lower oxygen content affect the combustion process, reducing the emission of CO, HC and NO_x. Neither is ethanol prone to pollute the environment, especially from the aspect of water pollution in case of accidental spillage.

The Estonian Bioethanol Cluster (Eesti Bioetanooli Klaster – EBK) was created to promote and develop the use of bioethanol in Estonia. The mission of EBK is to start the industry of bioethanol as renewable transport fuel by combining the potentials of local agricultural and oil shale energetics, thereby supporting the growth of Estonian export, agriculture, environment protection and energy security. The vision of EBK is the collection and treatment of biomass to produce bioethanol and renewable energy. Compared to fossil fuels, the advantages of bioethanol fuels are:

1) the by-product of bioethanol production (distillery residue) is considered a renewable fuel in the production of electricity as according to the calculations of EU regulations, it has no CO_2 emission;
2) In Estonia, bioethanol can be produced with minimal influence on land use, therefore a) it is relatively simple to ensure the raw materials necessary for a factory, and b) it is relatively simple to avoid the influence of the factors specified by the European Commission in 2010 (indirect land use change or ILUC), which would reduce the estimated greenhouse gas cutback and thereby the price of production.

EBK is planning to cooperate with the following institutions of higher education:

-Tallinn University of Technology's Department of Thermal Engineering has performed tests to determine the calorific value of distillery residue based biofuels and it will continue such activities in the future;

-Jõgeva Plant Breeding Institute helps to breed optimal crop varieties for producing bioethanol;

-Estonian University of Life Sciences performs studies concerning the biomass resources, bioenergy technologies and biofuel engine testing. As the first project, the possibilities of producing compound fertilisers from the residues of a bioethanol factory are studied. This should increase the independence of Estonian agriculture from imported fertilisers and they could become export items. Previously the Estonian University of Life Sciences' Institute of Technology has performed studies in the field of the production of biofuels (Küüt, et al. 2008; Menind, et al. 2009; Olt, et al. 2009).

Therefore, the production and use of bioethanol in Estonian conditions is one of the possibilities of switching to renewable fuels. It is clear that a complete transition to bioethanol produced from lignocellulose biomass as engine fuel is not realistic, however, partial use is possible. The main obstacles are:

1) the properties of bioethanol which influence the operation of an internal combustion engine;
2) the existence of local raw material resources and bioethanol production technologies which all affect the cost of used fuel (€ ha^{-1}).

Economic aspects. If biofuel is to be fostered, then the use of bioethanol presupposes the cost being not higher than conventional fuel. Therefore, this thesis explores the effect of biofuel on the engine output parameters and thereby on the cost of consumed fuel. In examining the data gathered during the study and the results of the analyses, a complex method is used which incorporates both production and use. The complex method can be used first and foremost in agriculture in comparison with transport companies, on the presumption that the raw material resources are sufficient for the production of bioethanol.

Research consists of chapters which describe the research activities and development to achive the aim of research. The thesis is mainly based on the following papers: I; II; III; IV; V, which have been listed in the part ”List of Orignal Publications”.

1. AIMS OF THE STUDY

1.1. Problem setup

The use of ethanol as a motor fuel is not widespread in Estonia even though it would ensure meeting the EU renewable energy requirements and improve the nation's energy security (independence). Most of the studies in the world concern pure ethanol (anhydrous, 99.5%) or its mixtures as fuel for internal combustion engines. The use of bioethanol as motor fuel is not economically sound due to the high amounts of energy required for the production of ethanol, in comparison with fossil fuels. The production of lower-grade bioethanol (LGBE) is simpler and probably cheaper. LGBE can be described by a moderate content of residues. At the same time, the energy value of LGBE is lower. At the production of LGBE, there remain certain impurities like fusel oils. Ethanol has several deficiencies which inhibit its use as the main motor fuel: low specific heat energy, the endothermic nature of the combustion process, bad solubility in other fuels, low lubricating properties, bad starting capabilities and high cost of pure ethanol's production. It is currently unknown what are the effects of impurities and content on the energy value and exhaust emission of bioethanol. The use of LGBE (100-, 90-, 80- and 70-proof alcohol) as motor fuel has been studied by Duck (Duck, 1945).

1.2. Aim of the thesis

The aim of this thesis is to develop a method for using LGBE as an internal combustion engine fuel in small agricultural companies.

The thesis will present the study results on the use of LGBE, produced from local lignocellulose raw material, as an additional fuel for the diesel engine. **The possible uses of the fuel mixture and its effects on the diesel engine and the combustion process will be studied.** The evaluation of the fuel mixture will include qualitative and quantitative methods for preparing mixtures. The quantitative ratio between fuel components and their possible uses in the diesel engine will be determined by optimising various methods of preparing mixtures. A local alternative fuel composition will be proposed and methods for its use will be evaluated using the motor method. **The physical and chemical properties of alternative fuel will be**

evaluated by measuring the engine combustion process indicators and engine output parameters. The thesis will make technical suggestions concerning the production of local alternative fuel's composition and its use in diesel engine. At the same time the prospects of one alternative fuel development are assessed. The novelty of the proposed solution lies in the dual fuel supply system which will ensure the injection of main fuel and a support system which will ensure the injection of additional fuel mixtures according to the engine load. This solution will ensure good engine starting and its operation under a wide range of modes. The additional fuel will be admitted to the cylinder through the inlet manifold by an additional fuel supply system.

The following tasks were assigned to fulfil the aim:

1) to give an overview of ethanol fuel production in the world;
2) to give an overview of ethanol fuel used as internal combustion engine fuel. To describe ethanol as a motor fuel and the engine's technical peculiarities while using ethanol as fuel (technical modifications, supplementary devices);
3) to choose a study method and testing methods;
4) to develop a technical solution for preparing an internal combustion engine fuel mixture on the basis of bioethanol and delivering this mixture to the cylinder (flexible-biofuel system);
5) to compile a calculated model for describing the production of bioethanol from lignocellulose biomass. The preparation of this model must include the price formation, taking into account the ethanol concentration;
6) to choose (prepare) characteristics for describing ethanol fuel mixtures as motor fuel on the basis of engine tests (developing test methods and characteristics on the basis of engine tests);
7) to prepare a calculated model for describing the change of cost of consumed fuel in € kWh^{-1}. This description must take into account the effect of biofuel with various ethanol concentrations on the fuel price and amounts in comparison to conventional fuels;
8) to give an overview of the possible uses of bioethanol as a biofuel in small-scale production. This overview requires preparing a model for describing relations between the fuel's specific cost and producer's price.

2. REVIEW OF THE LITERATURE

2.1. State of the art in bioethanol production

2.1.1. General information

Review of bioethanol production and usage as motor fuel has been composed by using publications of the author's contribution Ritslaid et al., 2010 and Küüt et al., 2011.

Bioethanol as motor fuel for internal combustion engines. Ethanol or ethyl alcohol (CH_3CH_2OH) with the molecular weight M = 46.7 is also known as alcoholic spirit, grain spirit, absolute alcohol and ethyl hydrate. Depending on its water content, method of production and final use, there are several ethanol products available on the market. 99% alcohol (mostly referred to as absolute alcohol) is used in preparing tinctures and pharmaceutical preparations, solvents and preservatives, antiseptics and perfumes. Ethanol represents a crucial functional component in the composition of alcoholic drinks produced by carbohydrate fermentation. If alcohol is used for purposes other than drinking, it is denatured with such additives as methanol, pyridine, formaldehyde, etc. (Ritslaid et al., 2010)
Denatured alcohol is used both industrially and as a motor fuel.

Physical properties. Ethanol in its pure form (absolute alcohol) is a colourless liquid. It is miscible in all proportions with water and also with ether, acetone, benzene, and some other organic solvents. Anhydrous alcohol is hygroscopic; at a water uptake of (0.3–0.4), a certain stability occurs. The main physical properties of anhydrous ethanol are the following (Ullmann, 1990a; Ritslaid et al., 2010):

Boiling point	78.39°C
Liquefaction point	–114.15°C
Refractive index n at 20°C	1.36048
Densities: d^{20}_{4}; d^{15}_{4};	0.79356; 0.78942
Flash point (in closed vessel)	13° C
Dynamic viscosity η	1.19 mPa·s
Heating value	
1) lower	29,895 kJ/kg
2) upper	29,964 kJ/kg

Azeotropic mixture consists of 95.57% ethanol and 4.43% water by volume. Therefore, normal distillation allows yield of 95.57% ethanol by volume. Further removal of water from the azeotropic mixture can be done either by using tertiary solvent, molecular sieves, membrane method or by some other method.

Chemical properties of ethanol are dominated by the functional –OH group, which can undergo many industrially important chemical reactions such as dehydration, halogenation, ester formation, and oxidation (Ullmann, 1990b; Ritslaid et al., 2010).

This chapter gives an overview of the various production methods of ethanol (mostly bioethanol). The production of ethanol requires choosing the raw material and production technology. The choice of raw material is of utmost importance as it affects whether the produced ethanol is renewable or not. This thesis studies various raw materials, most of which are based on renewable resources (lignocellulose materials). The choice of raw material must take into account the potential production volume in a region and the material's chemical and physical properties. The ethanol production technology should be chosen according to the properties of the raw material to ensure the efficiency of production and a clean environment.

The options in choosing the production technology are continuously increasing. According to the level of production technologies the fuels produced from renewable raw materials can be divided into generations (I–IV generation). The use of genetic engineering in production is being developed which should, under ideal circumstances, allow producing the fuel using microorganisms. Noubar Afeyan claims that his company (Joule Biotechnologies) possesses genetically modified photosynthesis-capable microorganisms which produce ethanol or biodiesel from carbon dioxide and water. These microorganisms live in photobioreactors. They do not need fresh water and the space they require for growing is relatively small compared to the space required by other biofuels. They give off fuel continuously; therefore fuel extraction is a continuous and simple process. On the basis of laboratory tests, Afeyan believes that one hectare could yield a hundred times more fuel than ethanol from a one-hectare maize field. According to Afeyan the price of this fuel is comparable to the price of conventional fossil fuels. (ERR)

The raw materials and production technology are very much interconnected as the production technology is chosen on the basis of the raw material, of course taking into account the requirements to fuel. The requirements to fuel depend on the engine's construction; however, this will be discussed more thoroughly in the second half of the thesis.

2.1.2. Ethanol's raw material

Generally, the raw materials for ethanol production are materials with carbohydrate content to which fermentation technology is applied. The main carbohydrates and their raw materials are (Ullmann 1990a):

1) starch
   - grains (maize, wheat, barley, sorghum / milo etc.)
   - potato
   - jatropha
   - cassava
2) sucrose
   - sugar cane
   - sugar beet
3) lactose
   - whey
4) cellulose
   - timber
   - straws
   - other lignocellulose materials.

Sugar cane is preferred as the source material in Brazil, maize in the USA, spoilt grain and sugar beet in Europe. In Asia (for example, Thailand) the most preferred raw material is manioc roots (cassava and tapioca). On the strength of International Energy Agency (IEA) projections, the production of biofuels could take the route outlined in Figure 2.1.

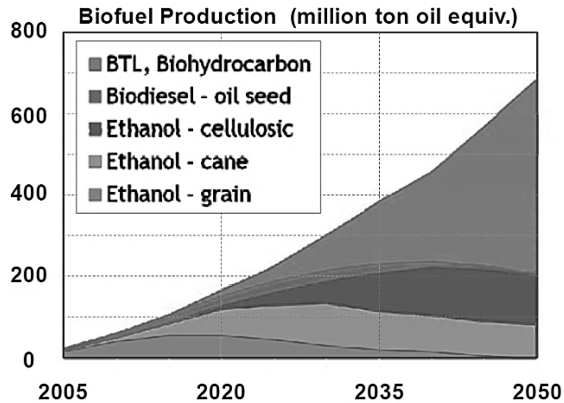

Figure 2.1. Estimated biofuel production by volume and composition (IEA 2008)

Biofuels obtained from renewable sources can be classified on the basis of their production technologies: biofuels of first and second generation and biofuels of third and fourth generation (Sims et al, 2008; Demirbas, 2009; Ritslaid et al, 2010). The first-generation fuels refer to biofuels made from plants rich in oil or sugar. The feedstock for such biofuels consists in oil plants (plant seeds) which are pressed to yield oil that can be processed into diesel fuels by esterification; sugar-containing feedstock is processed to yield ethyl alcohol, which is then used as gasoline additive or individual fuel. However, the production of first-generation biofuel is economically unreasonable because of discarding cellulose and hemicellulose—which constitute the majority of the carbon resource of the plants—in the course of the process. Furthermore, the biofuels of this generation also compete with food products intended for human consumption and animal fodder.

Second-generation biofuels (Biomass to Liquid) are made from organic materials such as straw, wood residues, agricultural residues (grains, potato), reclaimed wood, sawdust, and low-value timber. Feedstock also includes short rotation plants and trees (perennial grasses, short-rotation coppice) and quickly growing algae.

Biofuels of the third and fourth generation are produced from algae by using modern gene- and nanotechnologies.

Although the second-generation biofuels allow improving CO_2 balance, they do not yield a major benefit in comparison with the first-generation fuels, considering the high amount of fossil fuels used for their production.

Tables 2.1, 2.2 and 2.3 provide a summary of biofuels by generations, including respective feedstock and production processes (Sims et al, 2008; Demirbas, 2009; Ritslaid et al., 2010).

Table 2.1. First generation biofuels, their feedstock and technological processes (Sims et al, 2008; Ritslaid et al., 2010)

First-generation (conventional) biofuel		
Name	Biomass feedstock	Production process
Conventional bioethanol	Sugar beet, sugar cane, sugar sorghum	Hydrolysis & fermentation
Pure plant oil (PPO)	Oil plants (e.g. rape seed)	Cold-pressing/extraction
Rape methyl-/ethyl ester) RME/REE Fatty acids methyl/ethyl ester (FAME/FAEE)	Oil plants (e.g. rape/ turnip rape seeds, sunflower seeds, soy beans, etc.)	Cold-pressing/extraction/ transesterification
Fatty acids methyl/ ethyl ester (FAME/FAEE)	Biodiesel cooking and deep-fry grease	Transesterification
Upgraded biogas	(Wet) biomass	Anaerobic digestion
	Bioethanol	Chemical syntheses

Table 2.2. Second generation biofuels, their feedstock and technological processes (Sims et al, 2008; Ritslaid et al., 2010)

Second-generation biofuel			
Type of biofuel	Name	Biomass feedstock	Production process
Bioethanol	Cellulose ethanol	Lignocelluloses	Upgraded hydrolysis & fermentation
Synthetic biofuels	Mixed higher alcohols Bio-dimethyl ether	Lignocelluloses	Gasification + syntheses
Biodiesel (hybrid biodiesel from the first and second generation)	NExBTL	Plant oils and animal fats	Hydrogenation (Refining/ enrichment)
Biogas	SNG (Synthetic Natural Gas)	Lignocelluloses	Gasification & syntheses
Bio-hydrogen		Lignocelluloses	Gasification & syntheses or biological process

Table 2.3. Third and fourth generation biofuels, their feedstock and technological processes (Demirbas, 2009; Ritslaid et al., 2010)

Third-generation biofuel			
Type of biofuel	Name	Biomass feedstock	Production process
Biodiesel	*Oilgae* Algae diesel	*Algae*	Gene and nanotechnology & esterification
Fourth-generation biofuel			
Type of biofuel	Name	Biomass feedstock	Production process
Bio gasoline Bio jet fuel Biodiesel	Synthetic oil	Vegetable oil (CENTIA ™ oil from algae)	Hydrolytic conversion/deoxygenating

2.1.3. The principles of choosing energy crop

The choice of energy crop for raw material depends on the suitable habitat and purpose. One important aspect to consider in choosing an energy crop is the variety, since the cultivation techniques are generally the same within one species. The grain varieties most suitable for producing first generation bioethanol fuels are the varieties with high starch content, which is opposite to the food industry which prefers high protein content. The fertilisation system also affects the raw material properties.

According to previous study results, the most promising ethanol crops in Estonia are wheat, rye, triticale, potato, sugar beet (Jõgeva Plant Breeding Institute 2012).

In using all of the abovementioned species for producing liquid fuels, the yield quality may vary and it may contain less protein than the crop cultivated for food or fodder. It must be noted that the manufacturing cost of ethanol produced from grains is lower than from potatoes due to high storage and transport costs. In addition to the production of liquid fuels, all of these species are suitable for the production of biogas. As an extra value to grain production, the straws can be burned. The cultivation of sugar beet as energy crop in Estonia is limited due to the lack of production quota as the producer will not be subsidised contrary to producers in a country with quotas.
Natural grass plants: biomass harvested from permanent grasslands and (semi-)natural communities and wetlands.

The biomass which is cut for the purposes of nature preservation on some areas can be used for small-scale production of biogas or burning. Large scale use is limited by low yields in comparison with agricultural crops and thereby high transport costs. In Estonia, the possibilities of producing bioethanol from green plant mass have not been studied yet.

The republic's production of grain, which is about 600–760 thousand tonnes per year, is not enough to fulfil the needs for fodder, human food, seeds and industrial use; therefore additional grain is imported each year. Despite the fact that grain cannot be considered a source of biomass, grain (especially rye, considering the land resource) is still the most prospective source of industrial raw material. The growth area of oil crops (mostly rape) is below 50 thousand hectares a year. The yield of 70–80 thousand tonnes is not enough for the production of biodiesel. The land under fodder crops and permanent grasslands is utilised for fodder production. (Bioenergybaltic)

The most important factor in choosing the raw material is the energy crop's yield which becomes available after treatment. The yield is evaluated on the basis of the amount of produced bioethanol and its properties which determine its possible use as motor fuel. On average, one tonne of potatoes yields 80 litres of spirit, wheat 150 litres and maize 300 litres. Let us calculate the perspectives of replacing conventional fuel with bioethanol, taking into account various raw materials. For achieving this task, we must calculate the amount of lignocellulose bioethanol produced from local raw materials and compare these amounts to consumed conventional fuels (Table 2.4). Let us use *toe*'s in comparing the amounts.

Table 2.4. Amounts of consumed diesel fuel and petrol in transport and agricultural sector on the basis of statistics

Year	Sector	DF, thousand t	Petrol, thousand t	DF, thousand toe	Petrol, thousand toe
2008	Agricultural sector and fisheries sector	73	5	**73.73**	5.25
	Transport sector	179	4	180.79	4.2
	..railway transport	2	0	2.02	0
	..land transport	171	4	172.71	4.2
2009	Agricultural sector and fisheries sector	67	5	**67.67**	5.25
	Transport sector	185	3	186.85	3.15
	..railway transport	4	0	4,04	0
	..land transport	174	2	175.74	2.1
2010	Agricultural sector and fisheries sector	74	5	**74.74**	5.25
	Transport sector	217	4	219.17	4.2
	..railway transport	10	0	10.1	0
	..land transport	201	4	203.01	4.2

http://www.stat.ee/statistika.

DF, thousand toe and Petrol thousand toe – based on calculation.

Hypothetical resource of lignocellulose material (grass biomass) in Estonia and ethanol produced from it in a year.

There are about 120,000 hectares of unused grasslands in Estonia. One hectare is capable of producing 13 bales of hay. One bale weighs 120 kg. Therefore one hectare produces 1560 kg of hay and all the unused grasslands together produce 187,000 tonnes of hay. As 1 kg of hay (total solids 93.73%) yields 72–104 ml of bioethanol, then 187,200 tons of hay is capable of yielding 13,478,400–19,468,800 litres or *ca* 10,650–15,380 tons of bioethanol.

1 t bioethanol = 0.64 toe; 1 t petrol = 1.05 toe; 1 t diesel = 1.01 toe; 1 000 m^3 methane [0° C; 1 atm] = 0.95 toe.

The total annual bioethanol production is 6.82–9.84 thousand toe.

The equivalent to one tonne of oil (toe) is 41 868 megajoules (MJ).

Currently, the proportion of renewable energy fuel which originates from lignocellulose material from the grasslands is minimal in the transport sector. At the same time, the usage of bioethanol as motor fuel gives relevant results. According to the estimations, about 10% of the diesel fuel consumed in agriculture can be replaced by bioethanol. The use of biofuel in this way allows meeting the requirements of the directive 2009/28/EC.

The results of the test are far more positive when the biomethane which forms during the production of bioethanol is added here. In addition to the production of bioethanol from lignocellulose biomass (hay), our test production included about 48,859,200 m^3 of biomethane from the 120,000 hectares rated according to Table 1.10. Such an amount of biomethane (46,416 toe) is quite relevant in the transport sector. The relatively large amount of biomethane produced from the lignocellulose biomass can be explained by the low yield of bioethanol. On the basis of the data from the source FRN (2011) a simple analysis was performed to compare the test production of bioethanol to capacity production. The results for the production of bioethanol and biomethane using different raw materials have been given in Table 2.5. Differences can be noted in energy production per surface unit and in the comparison of fuel types using different raw materials. The difference in energy production per surface unit can be explained by a lower yield from the natural grasslands. However, the differences by fuel types in producing from cultivated plants (maize, grain) or lignocellulose grass biomass is problematic. On the basis of sources, the complex production of bioethanol and biomethane has a 47% lower energy content than the production of only biomethane from maize or grain. Our test production which involves rated production from lignocellulose biomass shows an 11.5% difference in the amount of energy produced depending on the type of fuel to be produced. It can be concluded that when using lignocellulose biomass, the type of fuel is not as important as when producing from maize and grain as the latter have an advantage in the production of biomethane.

Table. 2.5. Comparison of lignocellulose biomass with cultivated crops depending on the type of fuel

Raw material	Type of fuel for production	
	Bioethanol and biomethane MJ ha^{-1}	Biomethane MJ ha^{-1}
Maize, grain *1	35,404 + 22,760 = = 58,164	107,687
Natural grassland hay *2	2,449 + 16,240 = =18,689	20,844

*1 On the basis of data of Fachagentur Nachwachsende Rohstoffe e.V.
*2 On the basis of test results of the Estonian University of Life Sciences

It can be concluded from the analysis that when producing bioethanol from lignocellulose biomass, the production residues must be used for producing biomethane or a much more effective production technology must be developed.

2.1.4. Overview of ethanol production technologies

Bioethanol production studies in Estonian University of Life Sciences. The fuel laboratory of the Estonian University of Life Sciences has studied the possibilities for producing bioethanol. A method for evaluating the influence of pretreatment of raw material on the bioethanol yield has been developed here. The studied raw materials in the pretreatment include grass biomass and wheat straws in the production of bioethanol.

The influence on ethanol yield originating from grass biomass was studied using various materials and grades of crushing during the pretreatment (Tutt & Olt, 2010). Four different hay samples were used in the tests. The samples were first tested to analyse their content of cellulose, lignite and hemicellulose. The production method of bioethanol used on all samples included pretreatment, enzymatic hydrolysis, fermentation and distillation. During the pretreatment the material was crushed and treated in weak acid solution (1.5%, H_2SO_4) including heating for 90 minutes at a temperature of t_e = 121 °C. As the next step, the sample was cooled and pH was neutralised to the level of4–5 to use the enzyme *Accellerase 1500*. $Ca(OH)_2$ was used for the neutralisation. Most of the solid components of the sample decomposed during the hydrolysis, thereby forming a brown liquid. Hydrolysis was performed at the temperature t_h = 50 °C and with the length τ_e = 48 hours. The dry yeast *Saccharomyces cerevisiae* was used for the fermentation and the length of fermentation was five days. After that, a double distillation was performed and the ethanol content was determined in the distillate. The grade of crushing did not have a significant influence on the ethanol yield. The main factor influencing the ethanol yield was the content of cellulose. The higher the concentration of cellulose and the lower the concentration of lignin and hemicellulose, the higher the ethanol yield was for hay (80.4 g/kg). The largest divergence for cellulose amounts was 13.2% in the comparison of the samples (Table 2.6). Sources claim that by using various methods the divergence of yield has been as high as 90% (Wang, 2009).

Table 2.6. Ethanol yield of cellulose (Tutt & Olt, 2010)

Marker	Ethanol yield (g kg^{-1})	Ethanol yield (%)
P I	224.40	44.00
P II	211.26	41.42
P III	200.73	39.36
P IV	194.91	38.22

In the production of bioethanol from wheat straw, the influence of various pretreatment methods on the formation of sugars and ethanol production was studied (Tutt et al., 2012). Wheat straw was chosen as the study material because it is a wide-spread by-product in agricultural manufacturing and it does not compete with foodstuffs' production. The material was biochemically analysed in the laboratory (Table 2.7).

Table 2.7. Ash, hemiceiiuiose, cellulose and lignin contents in dry mass of wheat straw samples (Tutt et al., 2012)

Sample	Ash %	Hemicellulose %	Cellulose %	Lignin %
Wheat straw	3.57	31.01	46.47	7.94

The material was crushed to particles with the size 1–3 mm and it was treated with various acids and alkalis. Usually acid is the simplest method for treating the lignocellulose material. The acids used were sulphuric acid and nitric acid. Nitric acid gives good results in transforming cellulose to sugars; however, the results are worse than with sulphuric acid from the aspect of cost. As a result of acid use, certain inhibitors are formed as by-products which have an adverse influence on the fermentation process. The use of alkalis (NaOH, KOH and $Ca(OH)_2$) in pretreatment gives better results with less adverse influences on the fermentation process. Table 2.8 presents the test results on glucose and ethanol yield. Sulphuric acid (H_2SO_4 unrised) gave the best result in glucose yield. The best ethanol yield was given by potassium hydroxide (KOH).

Table 2.8. Glucose and ethanol yield of different pretreatment methods (Tutt et al., 2012)

Pretreatment method	Glucose yield (g kg^{-1})	Ethanol yield (g kg^{-1})
H_2SO_4 unrised	**276.7**	78.7
H_2SO_4 rised	267.3	92.0
KOH unrised	221.7	77.0
KOH rised	268.2	**104.3**
HCI rised	221.3	67.7
HNO_3 rised	316.7	95.0

By using different chemicals in the process of bioethanol production, the input and output parameters will be different. The differences are expressed in the amount of chemicals used in the raw material treatment process, the amount of work, the equipment and energy consumption. Upon choosing the production process, all these aspects have an influence on the manufacturing cost of ethanol.

In finding the total energetic value of the fuel produced from lignocellulose material, a complex solution was chosen, according to which initial production includes only bioethanol and the production residues are further used for producing methane gas. For assessing the methane gas yield from the production residue, analysis was performed in the Laboratory of Bio- and Environmental Chemistry of the Estonian University of Life Sciences. The production residue's chemical composition (Table 2.9) and methane yield (Table 2.10) was analysed in the liquid and dried residue.

Table 2.9. The chemical composition of bioethanol production residue and raw material

Sample Name	TS %	TN%	Cellulose %	Lignin%	Hemi-cellulose %	Ca%	P%	Mg%	K%
Slurry	9.67	0.246				0.239	0.023	0.01	0.079
Solid	93.73	1.056	32.92	4.96	25.53	0.597	0.155	0.169	1.089

Note: the results of the analysis have been presented for dry matter.

Table 2.10. Methane yield

Sample name	TS, %	VS, %TS	Methan, (L/KgTS)	Methan, (L/KgVS)
Slurry	9,67	75,78	279	368
Solid	93,73	93,04	340	365

Note: the amount of methane has been given at standard pressure and temperature (0°C; 1 atm)
TS (Total solids)
VS (Volatile solids)

Currently the factory cost of ethanol production from cellulose still exceeds the production cost of grain ethanol by 2.5–4 times. In June 2006 the price of bioethanol made of lignocellulose was 0.59 USD/l in the United States of America. The United States have set a goal of producing bioethanol from lignocellulose at the price of 0.28 USD/l by 2012 (Solomon, 2007). For example, currently (in the year 2012) the company *Novozymes* has announced the development of a new enzyme *Cellic CTec3* which should guarantee the factory cost of 0.53–0.66 USD/l for bioethanol produced from lignocellulose biomass. The company Novozymes has concluded an agreement to provide new enzymes for M&G Group who has opened a new factory in Crescentino, Italy, with production capacity of 45 million litres a year (Cardwell, 2012). Therefore, the goal set to reduce the price of manufacturing cost has not been achieved.

Ethanol impurities. Bioethanol and ethanol produced from fossil raw materials contain various impurities—fusel oils. Fusel oils are a poisonous, bitter and oily mixture which mostly consist of amyl alcohols, fatty acids and esters.

Fusel oils are products of industrial ethanol fermentation. A typical fusel oil contains about 60–70% amyl alcohol, to a lesser extent ethyl alcohol, n-propyl alcohol and isopropyl butyl alcohol and traces of other components. Fusel oils are used in the manufacture of paints, plastic, varnish and explosives. Due to its unpleasant smell and taste, this by-product is usually burned in manufacturing companies to satisfy the additional energy need (Fatima et al., 2008).

Dörmö has pointed out that it is possible to manufacture an environmental-safe biolubricant from fusel oil by enzymatic esterification in a solvent-free system. The biolubricant should be prepared in an integrated system by an esterification reaction of fusel oil and oleic acid, where immobilised Novozym 435 lipase enzyme is used as a biocatalyst (Dörmo et al., 2004).

Classification and Analysis of Ethanol Impurities

Bioethanol impurities:

1) Distillery residues contain spirit 7–10% by volume;
2) raw alcohol produced during distillation in the special column, which contains 88% ethanol by volume + fermentation process impurities (in our case, fusel in 94.5 % ethanol by volume);
3) second distillation—raw alcohol distillation results in rectified spirit with ethanol content of 96–96.5% by volume. (Rectified spirit is also produced directly in the continuous systems of distillery residue rectification; here the impurities are removed from the raw alcohol).

Impurities are the secondary and by-products of spirit fermentation. At a general content of 0.5% of impurities, more than 50 compounds have been identified from the following groups of chemicals: aldehydes and ketones, ethers, higher-order alcohols (fusel oils and acids).
Depending on the volatility of the impurities, they are divided into volatile, low-volatile and intermediate impurities.

The volatile impurities boil at a temperature which is lower than that of ethanol. These include aldehydes (acetic acids etc.), ethers (formic acid ethyl ester, acetic acid methyl ester etc.) and methyl alcohol.

The low volatile impurities boil at a temperature which is higher than that of ethanol. These include mostly fusel oils, i.e. higher-order alcohols—propyl-, isopropyl-, butyl-, isobutyl-, amyl-, isoamyl- and other alcohols. Furfurol, acetals and some other compounds also belong to this group.

The intermediate impurities are the compounds which are the hardest and most labour-consuming to remove. Depending on the distillation temperature they can be either volatile or low-volatile impurities. This group includes iso- or acic ethyl-, iso-valerianic acid ethyl-, acetic acid iso-amyl- and iso-valeric acid iso-amyl esters.

In some cases raw alcohol is treated chemically before rectification to remove the impurities: NaOH saponifies esters and turns them to salts of volatile acids; $KMnO_4$ oxidises aldehydes to non-intermediate impurities.

Russian scientists (Мураташин А.М. et al., 1998; Помазанов В.В., et al., 2000) have studied the ethanol impurities thoroughly, counting a total of 250 compounds. Ethanol's raw material can be evaluated by determining the content of ethanol using gas chromatography–mass spectrometry.

Scientists believe that it can be determined whether ethanol is of biological or synthetic origin and which raw material was used. One of the most promising methods is the analysis of ethyl alcohol's gas chromatography–mass spectrometry differences. The gas chromatography method allows analysing the concentration of microelements within a certain range as specified by the standard GOST 30536-97. The measured impurities have been divided into tables according to the requirements of the standards GOST 5964-93 "*Спирт этиловый. Правила приемки и методы анализа*" and GOST 18300-87 "*Спирт этиловый ректификованный технический*". The measured impurities have been presented by samples. The samples include synthetic ethanol and ethanol produced from grapes, maize, molasses, wheat, rye, triticale (hybrid of wheat and rye) and sugar beet molasses in the industrial plants of Bashkortostan, Kursk, Orenburg, Samara, Sverdlovsk and Krasnodar regions in Russia and Brest, Minsk and Mogilev regions in Belarus. To ensure the validity of results, the studied samples included not only purified alcohol but also crude oil alcohol.

2.2. Study of potential uses for ethanol as motor fuel

2.2.1. Using bioethanol as motor fuel

The use of ethanol as motor fuel has been studied very thoroughly in the 20th century. Ethanol is used as motor fuel or additive to the main fuel in several countries like Brazil, Bolivia, Uruguay, Norway, Sweden and Finland. Fuel production technologies have been developed for the use of pure ethanol and ethanol mixed with motor fuel or diesel fuel in internal combustion engines. Despite all the studies and already existing technologies, the modern European Community includes several countries where alternative fuels are not used sufficiently in the production sector. Therefore, there are several objective factors and specific peculiarities which impede the wide-spread use of ethanol fuel in various countries, requiring further studies.

The most common biofuel in the world is bioethanol, which accounts for more than 90% of used biofuels. World's largest producers of bioethanol are Brazil and the USA, Spain, India and Turkey. The most successful European country in using bioethanol is Sweden where all of the Stockholm urban buses have been running on ethanol for more than 20 years.

In parallel to the aforesaid it is necessary to promote the use of bioethanol made from local renewable resources in Estonia as well. Until now attention has been paid mainly to biodiesel as alternative fuel. The research carried out in the Estonian University of Life Sciences aims at the production of ethanol in a farm environment, its feasibility and use as motor fuel (Küüt et al., 2011). The fuel supply system for using biofuels on internal combustion engines is being developed (Ilves et al., 2012).

The options for using bioethanol in the transport sector are the following:

1) direct mixtures with petrol,
2) direct mixtures with diesel fuel,
3) autonomous fuel (E85-E95),
4) source for oxygenates,

2.2.2. Direct mixtures with petrol

Mixtures with petrol are the most important applications of ethanol in the fuel sector. In Brazil, the ratio of bioethanol in petrol is 20–25% by volume. The ratio of bioethanol depends on the possibilities and price; a content of 10% is common in countries such as the USA, China, Thailand or Australia. Even in Estonia (as a member of the EU) a total content of 10% of oxygenates is allowed in motor vehicle petrol and the EU motor vehicle petrol directive 98/70/EC and 2003/17/EC allow a total of 5% of biopetrol in petrol.

Although ethanol blends completely with hydrocarbons, the ethanol mixtures need logistic solutions for the production of mixtures as ethanol has two peculiarities:

1) ethanol has a greater affinity towards water than hydrocarbons and ethanol components are less polar,
2) ethanol and hydrocarbons form non-ideal mixtures, which causes the physical and chemical properties of blended fuel mixtures (i.e. motor vehicle fuel) to behave non-linearly.

Blending ethanol with petrol increases the mixture's tolerance towards water. This means that ethanol may act as a "solvent" by keeping the water molecules in the mixture. If the water content rises above a critical threshold, then the water phase separates from the carbon phase. Ethanol's high affinity towards water may cause the ethanol molecules to move to the water phase. While ethanol works as an octane number booster, the hydrocarbon phase with residues removes the antiknock properties, thereby affecting adversely the quality of the fuel. Therefore, the handling of direct mixtures requires careful avoiding of water in the distribution system. This has been studied by, for example, German DGMK (Deutsche Wissenschaftliche Gesellschaft für Erdöl, Erdgas und Kohle) (Walther, 2005).

The non-linear physical and chemical properties of ethanol are important in blended mixtures which contain a minor part of ethanol. Despite the fact that pure ethanol has a low vapour pressure (dry vapour pressure equivalent, DVPE = 15.5 kPa), the vapour pressure in mixtures with gasoline increase considerably at low concentrations (up to 5%).

Keeping in mind the required fuel specification, the base petrol is modified by removing most of the volatile hydrocarbons (C_4/C_5 products) from the mixture despite the fact the non-linear properties

manifest much less in higher concentration mixtures. Depending on the composition of petrol, blending is used for obtaining a blended mixture with a vapour pressure similar to the original ethanol with the concentrations 20–50%.
In some countries the oil companies invest in fuel storage for optimising the fuel logistics cost. Therefore it becomes evident that the vapour pressure increases considerably during the mixing of fuels with and without ethanol. This effect is known as the "mixing effect".

This effect can be avoided by either adding ethanol to the fuel at a high concentration or adding ethanol to low vapour pressure fuel.

2.2.3. Direct mixtures with diesel fuel

The mixing of bioethanol and diesel fuel is currently not widespread, however, it is known that adding ethanol to diesel fuel will reduce exhaust gas emission by up to 40% in heavy load vehicles. The adding of bioethanol to diesel fuel is not very widespread in the EU as there is no general specification for it. Specifications have been developed in Sweden and there exist two specifications for fuels Etamax D and Etamix D (BioScopes, 2006). Etamax D is ethanol (95% by volume) with ignition improver. Etamix D is a diesel fuel mixture with 15% ethanol. These fuels are produced by the Swedish company Sekab (Svensk Etanolkemi AB) (Etek Etanolteknik AB, 2010).

The ethanol fuel diesohol for pressure-ignited engines consists of diesel fuel (84.5%), hydrated bioethanol (15%) and emulsifier (0.5%). The hydrated bioethanol means here that the water content is less than 2%. The emulsifiers used in the mixing of diesel fuel and water are styrenebutadiene copolumer and polyethyleneoxide-polystyrene copolymer (Demirbas, 2009).

Adding ethanol to diesel fuel will reduce two of the quality indicators: flash point and cetane number. The decrease of cetane number is compensated a special additive—cetane number booster. The considerably lower flash point requires monitoring and the safety measures should be taken to protect vehicle parts.

The effects of ethanol fuel on engine output performance parameters are diverse and depend on the engine and fuel supply system design. A group of scientists (Nagarajan et al., 2001) has pointed out the differences in output parameters and combustion process for using various technical solutions for igniting the ethanol fuel. The solutions include: dual system fuel supply system, ignition by ignition booster, glowplugs and spark ignition. Generally, the thermal efficiency has increased at full power. The use of glowplugs gives weaker results than other solutions. Generally, the ignition delay becomes longer but best results are achieved by the use of spark ignition. CO emission will increase in case of all the abovementioned solutions, except for ignition booster. HC and NOx-s are higher and diesel soot content is lower for all solutions.

In the analysis of engine output parameters, the best results were given by a dual fuel supply system where the ethanol fuel is admitted by the fumigation method). Its main principle is to break fuel into as small particles as possible to foster the combustion process. Various ethanol-diesel fuel ratios were studied and the best results were produced by a mixture with 20% ethanol. The fumigation method enables to reduce CO emission by 2.5% (Figure 2.2), HC emission by 5.6% and smoke coeficient by 20% compering to blended ethanol method. At the same time the engine thermal efficiency increased by 2.3% using the fumigation method (Figure 2.3). (Abu-Qudais et al 2000)

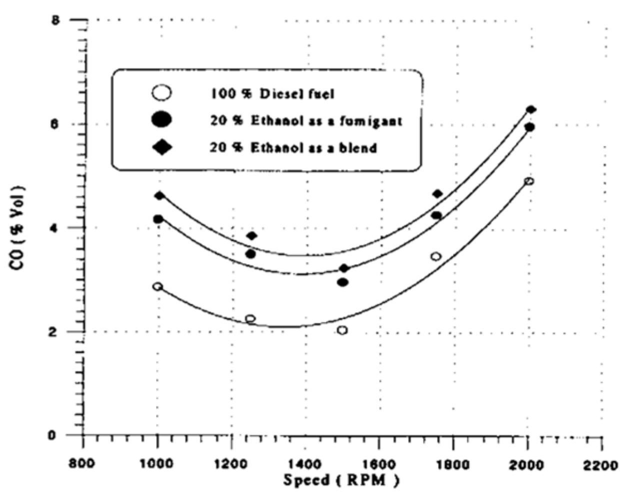

Figure 2.2. CO emissions versus speed for ethanol fumication and for fuel blends (Abu-Qudais et al 2000)

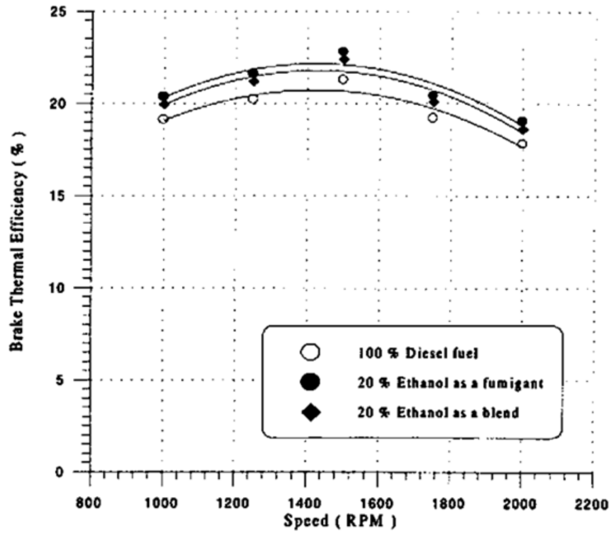

Figure 2.3. Brake thermal efficiency versus speed for ethanol fumication and for fuel blends (Abu-Qudais et al 2000)

2.2.4. Bioethanol as autonomous fuel

Continuous developments in the so-called "Flexi Fuel Vehicles" (*FFV*) have enabled the use of mixtures with high ethanol-content, namely, fuels with 85% bioethanol content. These vehicles may operate on any mixture of ethanol and gasoline in any ratio. The sensors detect the oxygen content of the fuel and engine operating parameters shall be adjusted accordingly.

E 85 contains 85% ethanol and 15% regular gasoline and it has been introduced to various fuel markets worldwide. In March 2006, the majority (80%) of the vehicles for such fuel were sold in Brazil. Many car manufacturers in Brazil have discontinued the production of gasoline vehicles for the local market altogether. Flexi fuel vehicles can operate on E85, which is the most commonly used fuel, or on any mixtures with the maximum ethanol content of 85%. This represents a major advantage of these vehicles as they are truly flexible and do not depend on the type of fuel; they also consume less energy than other alternative sources.

"Clausthal Technical University, Kassel University and IFOS Kaiserslautern indicate that engine life is impaired by operation with E85. For the timing chain as an indicator of tribological processes in this investigation, the rate of wear increases by 20%" (Schwarze et al., 2010).

Ethanol is chemically more active than gasoline with regard to polymers and metals, thus the engine parts directly exposed to ethanol have to be made of special materials. In addition to that, a heated engine block is required for cold starting.

In Brazil, such cars have assumed significant importance on the market as the majority of the car manufacturers offer flexi fuel vehicles. The proportion of manufacturing new flexi fuel vehicles has exceeded 80%, thus opening a huge market for ethanol fuels.

The European Committee for Standardization—CEN—has developed standardised requirements applicable in Europe today.

Vehicle manufacturers such as Ford and General Motors (Saab) have introduced their own products to the European markets. Sweden has been a pioneer in Europe with more than 16,000 flexi fuel vehicles sold already in 2006 (Handbook of Fuel, 2009). Before the Ford Focus with flexi fuel option was introduced in Sweden, mass production featured only one model that operated on a gasoline mixture with high ethanol content. It was the flexi fuel Ford Taurus, a car that belonged to the same category as Volvo S80 and Saab 95. The goal was to register 4,000 flexi fuel Ford Focus cars nationwide by summer 2010. This goal was set within the framework of Swedish FFV Buyer Consortium BAFF flexi fuel project. (BAFF, 2010)

E95. High-load vehicles are manufactured in Sweden, which use ethanol as fuel (95% ethanol + 5% additive for improving ignition). Scania has developed high-load compression (pressure) ignition engines for vehicles capable of running on ethanol. These engines have been tested and used in buses of municipal transport companies in Stockholm and elsewhere for over 20 years. For instance, Scania has manufactured approximately 700 ethanol-fuelled buses; more than 600 of them operate in Swedish cities (Green Car Congress, 2010). Scania has opened a commercial service for ethanol buses in Great Britain, Spain, Italy, Belgium, Norway, etc.

Main advantages for using ethanol in vehicles at high loads:

1. replacement of diesel fuel with ethanol gives better results in reducing NOx emission and carbon black components than replacement of gasoline with ethanol;
2. in Europe the quality requirements for diesel fuel have increased immensely, thus the replacement of diesel fuel with ethanol complies with the requirements set for fuel;
3. improvement in consumer awareness of using biofuels.

The tests carried out in Sweden have showed significant reduction in CO, NOx and carbon black components, as shown in Table 2.11.

Table 2.11. Reduction in exhaust emissions in case of bioethanol in comparison with regular diesel fuel emissions (Egebäck, 2004)

	NOx	CO	HC	PM	CO_2
ESC	–28%	–80%	–50%	–60%	Ethanol from wheat –82% Ethanol from wood –88% Ethanol from sugar cane –90%

As ethanol lacks lubricating properties, it is necessary to add an additive to the fuel to improve lubrication.

2.3. Engine characteristics

2.3.1. Engine power and economic characteristics

The evaluation of the power and economic parameters of an Otto engine include speed characteristics to find relations which depend on engine crankshaft rotational speed n_e. The engine parameters are net power P_e, torque T_e, fuel consumption in one hour B_f, specific fuel consumption b_e, mean effective pressure p_e, and underpressure in inlet manifold Δp. If the measurement is performed not at full power and fuel injection and ignition timing are not adjusted to optimum, then the results classify as partial use external characteristics. The results are presented in the graph as the function:

$$P_e, T_e, B_f, b_e, p_e, \Delta p = f(n_e). \quad 2.1$$

The load characteristics of an Otto engine are tested at crankshaft's constant rotational speed. The mixing valve adjuster handle position is changed in increments of 10% according to the change in power. This characteristic describes the dependence of engine load on fuel consumption, fuel consumption in one hour and specific fuel consumption. The results are presented in the graph as the function which depends on crankshaft rotational speed n_e:

$$P_e, T_e, B_f, b_e = f(n_e). \qquad 2.2$$

The diesel engine load characteristics are fuel consumption in one hour B_f, air consumption B_a, air excess ratio λ_a, specific fuel consumption b_e depending on the engine power, torque or mean effective pressure. During the test, load is applied to the engine while fuel injection increases in increments until the maximum amount at a constant crankshaft rotational speed. The results are presented in the graph as the function:

$$B_a, B_f, b_e, \eta_v, \eta_i, \lambda_a = f(p_e). \qquad 2.3$$

The diesel engine regulation characteristic describes the functional relation between fuel injection angle and power and economic parameters (power P_e, fuel consumption in one hour B_f and specific fuel consumption b_e):

$$P_e, B_f, b_e = f(a_{st}) \qquad 2.4$$

Equations of engine parameters
Net power:

$$P_e = i\tau_t n_e p_{me} V_h, \qquad 2.5$$

where i – number of cylinders;
τ_t – number of strokes (2 strokes = 1 and 4 strokes = 0.5);
n_e – number of crankshaft revolutions;
$p_{m,e}$ – engine effective pressure;
V_h – cylinder volume.

$$P_e = 2\pi n_e T_e, \qquad 2.6$$

where T_e – engine torque.

Induced total power:

$$P_i = i\tau_t n p_{mi} V_h, \qquad 2.7$$

where p_{mi} – engine indicated pressure;

$$P_i = P_e + P_m \qquad 2.8$$

Mechanical efficiency η_m:

$$\eta_m = \frac{\eta_e}{\eta_i} = \frac{P_e}{P_e + P_m} = \frac{P_e}{P_i} = \frac{p_{me}}{p_{mi}} \qquad 2.9$$

Mean effective pressure:

$$p_{me} = p_{mi} - p_m \qquad 2.10$$

Mean mechanic loss pressure:

$$p_m = \frac{\pi \tau_t T_c}{(iV_h)} \qquad 2.11$$

Engine indicated efficiency:

$$\eta_i = \frac{1}{b_{ei} Q_{HV}} \qquad 2.12$$

Specific fuel consumption:

$$b_e = \frac{B_f}{P_e} = \frac{1}{\eta_e Q_{HV}}, \qquad 2.13$$

where η_e – engine efficiency;
Q_{HV} – fuel heating value (lower);
B_f – fuel consumption.

Fuel consumption:

$$B_f = m_f \tau_d, \qquad 2.14$$

where m_f – amount of fuel consumed during the test;
τ_d – duration of test.

Engine efficiency

Engine thermal efficiency:

$$\eta_t = \frac{\eta_f}{\eta_c}, \qquad 2.15$$

where η_f – fuel conversion efficiency;

η_c – combustion efficiency (0,95…0,98)

Fuel conversion efficiency:

$$\eta_f = \frac{W}{m_{fc} Q_{HV}}, \qquad 2.16$$

where W – work of one cycle;

m_{fc} – mass of fuel for one cycle.

Diesel engine injection pump section's mean cyclic injection:

$$V_{f.fp} = \frac{\sum_{i_1=1}^{i_1} V_i}{n_c}, \qquad 2.17$$

where V_i – output of i th section;

i_l – number of sections in the injection pump;

n_c – total number of cycles.

$$n_c = n_{cam} i_1, \qquad 2.18$$

where n_{cam} – injection pump camshaft's rotational speed.

Diesel engine injection pump's fuel consumption:

$$B_{f.fp} = \sum_{i_1=1}^{i_1} V_i \rho_f, \qquad 2.19$$

where ρ_f – fuel density.

Injection during cycle in the engine test:

$$V_{f.en} = \frac{B_{f.en}}{i_l \cdot n_{cam} \cdot \rho_f}, \qquad 2.20$$

where $B_{f.en}$ – fuel consumption in the engine test.

Coeffcient *k* of cyclic injection in the comparison of injection pump and engine test:

$$k = \frac{V_{f.fp}}{V_{f.en}} \qquad 2.21$$

2.3.2. Exhaust emission characteristics

The measuring method MM 02–2005 is used for measuring exhaust emissions of spark ignition engines during technical inspection. According to this method, the content of contaminants in the exhaust emission are inspected and measured using a spectrograph type gas analyser. The device will register, analyse, record and print out the results for carbon monoxide (CO), carbon dioxide (CO_2) and oxygen (O_2) percentage by volume and hydrocarbon (HC) by parts per million by volume (ppm) in the exhaust emission. The excess-air coefficient is calculated using the measured data. For pressure-ignited engines, the exhaust emission's opacity is measured using the measuring method MM 04–2005. The measuring device opacimeter will determine the exhaust emission's transparency in comparison to the transparency of clean air. Opacity is described by the coefficient of absorption k_a, m^{-1}. The measuring method is based on the laws of Lambert, Borger and Bear. The measuring methods have been developed by the Estonian ARK.

Scientific research establishments have developed various standards for evaluating and comparing the exhaust emissions of various engines and fuels. The most widespread standard is ISO 8178 which contains the vehicle test method *Non-Road Steady Cycle* (NRSC). The preparation of characteristics depends on the measurements on various load modes and crankshaft rotational speeds (Table 2.12). The Figure 2.4 shows the main portfolio of measurement characteristics of NRSC from the standard ISO 8178 Type C1, which is suitable for measuring the exhaust emissions of vehicles in agriculture.

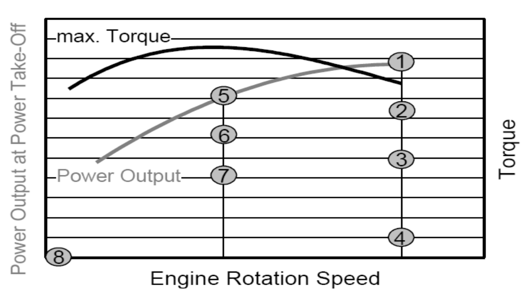

Figure 2.4. Test modes within the engine operating map according to ISO 8178 for emission testing (Thuneke et al., 2011)

Table. 2.12. The part of engine weighting factors, load and speed of ISO 8178 test cycles (Dieselnet)

Mode number	1	2	3	4	5	6	7	8	9	10	11
Torque, %	100	75	50	25	10	100	75	50	25	10	0
Speed	Rated speed					Intermediate speed				Low idle	
Off-road vehicles											
Type C1	0.15	0.15	0.15	-	0.10	0.10	0.10	0.10	-	-	0.15
Type C2	-	-	-	0.06	-	0.02	0.05	0.32	0.30	0.10	0.15

Notes:

- Engine torque is expressed in percent of the maximum available torque at a given engine speed
- Rated speed is the speed at which the manufacturer specifies the rated engine power
- Intermediate speed is the speed corresponding to the peak engine torque

3. MATERIALS AND METHODS

3.1. Choice of study method

This is an applied study and therefore it is based on tests. The test conditions have been determined before as the number of measurements is limited both for production and use. The analysis of test data uses the standard regression model. As a result, the characteristics and the model of using bioethanol have been compiled according to the data.

The first task in achieving the aim was to start a test production to evaluate the production price of low grade bioethanol produced from lignocellulose biomass in small-scale production. The production tests were performed with pilot-scale equipment. The relation between the production's price formation of various quality grades of bioethanol was analysed in the evaluation of measurement results.

The study of the possibilities of using bioethanol in compression-ignition internal combustion engines included pre-tests which characterised the reliability of fuel supply system on the basis of wear. On the basis of test results, the method for using bioethanol in compression-ignition internal combustion engines was chosen.

The technical solution of fuel supply for using bioethanol in spark-ignition internal combustion engines was not modified. The fuel line was partially replaced and electronic accessories were used to modify the internal combustion engine's input parameters.

During the studies it became obvious that an additional fuel supply device must be developed. The goal was to develop an initial prototype of such a device. A theoretic study and practical tests were carried out to find the developed device's working parameters under laboratory conditions.

To evaluate the effect of bioethanol's grade on the engine output parameters, practical tests were performed by using bioethanols originating from various production methods. The tests were performed using both spark-ignition and compression-ignition internal combustion engines. As a comparative study, measurement results from similar conditions were used and characteristics were prepared. The analysis of comparison characteristics is necessary for confirming the possibility that in performing the tests of the power and economic parameters of internal combustion engine, high-grade ethanol mixed with distilled water may be used to imitate low grade ethanol.

The engine tests needed for preparing the necessary characteristics were performed on test bench in laboratory conditions.

Speed characteristics $f_{(ne)}$ were used for measuring and evaluating the output parameters of spark-ignition internal combustion engine. Load characteristics $f_{(Te)}$ were used for measuring and evaluating the output parameters of compression-ignition internal combustion engine.
A characteristic had to be prepared to evaluate the cost of consumed fuel, which would describe the fuel consumption B_f, and specific consumption b_e, according to the specifics of the tractor's or vehicle's operation. In using agricultural machinery, the operational speed of a machine and/or its main unit speed are of utmost importance. Therefore, one of the constants is engine crankshaft rotational speed ne at the performance of a specific job A, or at engine's constant speed at a constant torque T_e. This characteristic is used for describing the functional relation between fuel consumption and specific consumption and ethanol concentration a_c in bioethanol:

$$B_f = f(a_c) \qquad 3.1$$

$$b_e = f(a_c) \qquad 3.2$$

The characteristics for describing fuel consumption and specific fuel consumption are prepared on the basis of measurement results received from the preparation of load characteristics.

3.2. Study objects

The study objects comprise of bioethanols with various grades (Low Grade Ethanol – LGE). In this study, *low grade bioethanol* means any liquid which has lower ethanol content than anhydrous ethanol (99.7% by volume) irrespective of its production method. The engine tests include liquids which have an ethanol content of 60% to 96.3%. Low grade bioethanol is referred to as farmstead ethanol in the publications.

A previous study performed by the authors (Olt, et al., 2009a) provided engine tests with bioethanol, gasoline 95, E15, E30, E50, and E85. Analogous studies have been performed in the Latvian University of Agriculture to develop testing methods (Dukulis, et al. 2009). Pursuant to the test protocol *Analytical report SB 090701* by Analiit-AA in 2009, concerning bioethanol E85 used in engine tests, it appeared that bioethanol that was used for producing E85 was manufactured on the basis of the production licence of the Republic of Latvia LV No. 1000380004. The test protocol reveals that the bioethanol sold in the filling station was produced from very pure 99.6% ethanol, which does not contain other oxygenates (ethers, methanol, higher alcohols, etc.). This is clearly a waste of resources because the ethanol used as motor fuel does not require the purity of potable spirit. Pursuant to standards bioethanol may contain up to 5.2% ethers by volume, 2% higher (C3-C8) alcohols by volume and the minimum ethanol content in bioethanol E85 is 75%. Another important factor is that higher alcohols increase the energetic value of bioethanol. According to the standard, added unleaded gasoline content may be within the range of 14 to 22% by volume. (European Standard CWA 15293, 2009; Küüt et al., 2012c).

The next part will discuss the LGBE-s used in this study and gives their characterisations.

1. Low grade bioethanol (LGBE) produced in the Estonian University of Life Sciences (Küüt et al., 2012c). The raw material for this bioethanol is green lignocellulose biomass. The production of this LGBE was used to study the production price formation and perform comparison tests for evaluating the effect of residues on pressure ignited internal combustion engines. Liquids with minimal ethanol content (60% by volume) were chosen for testing to ensure maximum content of residues and that the engine would still be capable of stable running. The results concerning power and economic parameters have been presented in the fourth part of this thesis. The production of bioethanol from lignocellulose material has been described in the literature review section and the formation of bioethanol's price has been described in the descriptive part. The analysis of production price was performed for bioethanol produced from hay. A comparative

analysis was performed on the properties of tested ethanol fuels, which includes the results of residue analysis and is displayed in figures in Table 3.1.

Table 3.1. The chemical and physical characteristics of ethanol and LGBE (Küüt et al., 2012c)

Property	Testing method	DLGBE 60%	LGBE 58,9%
Density, g/cm^3 20 ^{o}C	DIN EN ISO 12185	0,908	0,917
Recrement, g/l	ASTM D381-04	**0.0081**	**0.050**
Colour	-	Colourless	Yellow
Flash point, ^{o}C	DIN EN ISO 2719	24,5	24,5
Vapor pressure, kPa 37.5° C	ASTM D5191-07	14,5	14,5

Perennial grass, dried and stored in the previous summer, was used as lignocellulosic material. Biochemical tests for assessing lignin, cellulose and hemicellulose content of the material were carried out in the laboratory of the Estonian University of Life Sciences, the results are presented in Table 3.2

Table 3.2. Test results of lignocellulosic material used for producing LGBE (Küüt et al., 2012c)

Sample	Dry ingredient%	Lignin%	Cellulose%	Hemicellulose%
Perennial grass	94.78	4.96	32.92	25.53

2. Third fraction bioethanol (Küüt et al., 2011) from large-scale production which originates from American maise—LGBE-III. This LGBE-III is described by high residue content, especially fusel oils. Organoleptic analysis confirms the existence of fusel oils (C3-C5 Spirits), organic acids (butyric acid, isobutyric acid), esters (isobutyric acid, ethyl ester; isovalerian acid, ethyl ester) etc. in bioethanol. This studied bioethanol was used for performing comparative tests with compression-ignition internal combustion engines for evaluating the effect of residues. Tables 3.3 and 3.4 provide the parameters for bioethanol E85 and LGBE-III and the European requirements for E85, and requirements for fuel ethanol in the USA. The laboratory also determined the density, fraction composition, ethanol content, and other parameters of LGBE-III (see Table 3.4). It appears from the

table that in terms of ethanol and methanol content, fraction composition (except for the deposit at the bottom of the piston) the LGBE-III complies with all the requirements. However, resins and water content need to be reduced. Determination of higher alcohols was complicated because the gas chromatographic method (EN 13132) did not allow product analysis. The results of the analysis reveal that produced bioethanol needs better distillation to remove heavier, default compounds, and reduce excess water content by using the suitable method.

Table 3.3. Comparison of initial ethanol for producing bioethanol E85 and biogasoline with LGBE-III. (Küüt et al., 2011)

Property	Units	Limits E85*	Test method	Bioethanol E85 of Statoil petrol station**	Denaturated ethanol ASTM D 4806	Bioethanol farmstead ***
Higher alcohols (C3-C8)	V/V %	max 2.0	EN1601/EN 13132	0		
Ethanol content	V/V%				92.1	94.51
Ethanol+higher alcohols	V/V%	min 75		85,1		
Methanol	V/V %	max 1.0	EN1601/EN 13132	0	max 0.5	0.55
Ethers (5 or more atoms)	V/V %	max 5,2	EN1601/EN 13132	2.49		
Premium grade unleaded petrol as specified by EN228:2008	V/V %	14-22	Calculated	14.64		
Water content	V/V %	max 0.3	ASTM E 1064	0.265	1.0	6.94
Solvent washed gums: unwashed washed	mg/100 ml	5.0				 65.0 33.0
Inorganic chloride content	mg/l	max 1.0	ISO/6227/ ASTMD 512	0.192	max 32 mg/l	

*Limits preferred SVENSK STANDARD SS 155480:2006 and European Standard CWA 15293:2005.
**- analyzed Analiit-AA OÜ
***- analyzed Saybolt Eesti AS. Tested ex 95% fraction and water content not deducted.

Table 3.4. Other properties of LGBE-III (Küüt et al., 2011)

Property	Test method	Unit	Result	Limits
Density**, 15 ^oC	ASTM D 4052	kg/m^3	816.2	No norms
Water content by Karl Fischer*		V/V%	6.94	0.3 – (CWA15293:2005) 1,0 - (ASTM D 4806)
Ethanol content*	ASTM D 5501	V/V %	94.51	min 92.1
Methanol content*	ASTM D 5501	V/V %	0.55	max 0.5
Distillation**	ASTM D 3405	V/V %		
Initial boiling point, ^oC			75.5	
10% (V/V) ,^oC			77	
20% (V/V), ^oC			78	
50% (V/V), ^oC			78	
60% (V/V), ^oC			78.0	
70% (V/V), ^oC			78.5	
80% (V/V), ^oC			78.5	
90% (V/V), ^oC			79.0	
95% (V/V), ^oC			80.0	
98% (V/V), ^oC			83.0	
99% (V/V), ^oC			120.0	
Final boiling point, ^oC			123.0	
Residue, ml			0.4; brown organic residue	
Acidity, (as acetic acid CH_3COOH)**, % (m/m)	ASTM D 1613		0,00575	0,005 – CWA15293:2005 0,007 – ASTM D 4806

*- analyzed at Saybolt Eesti AS

**-analyzed in the fuels and lubricants laboratory of the Estonian University of Life Sciences

3. Various low grade mixtures of ethanol and water produced on the basis of surgical spirit – DLGE (Küüt et al., 2012c). This liquid is characterised by high water content in comparison to the residues. DLGE fuel mixtures were used for evaluating and analysing the compression-ignition engine output parameters and consumed fuel cost by replacing LGBE (Küüt et al., 2012a).

The study objects were particular spark- and compression-ignition internal combustion engines *A4 ADR* and *D-120*. The engine specifications have been given in the fourth chapter in the test description.

The programme for applied studies and development works was as follows:

1. to find a solution for producing a fuel mixture in laboratory conditions and to study the possibilities of using fuel mixture and its properties in internal combustion engines;
2. to study the influence of LGBE in an internal combustion engine (outgoing parameters);
3. to develop a method for preparing the fuel mixture and a system for delivering fuel to the combustion chamber of an internal combustion engine;
4. to study the influence of bioethanol on the fuel supply system's wearing parts, especially the parts of high-pressure pumps;
5. to study the formation of the price of bioethanol fuels with various concentrations.

3.3. Tests

3.3.1. Impact of ethanol on the fuel injection pump of diesel engine

The use of ethanol in the diesel engine fuel supply system is complicated, because the lubricating properties and viscosity of ethanol are significantly lower than that of diesel fuel. Another problem arises from the water content in the fuel, which causes corrosion (Govindarjan, 2008; Olt et al., 2011b). Due to the aforesaid reasons certain parts of the diesel engine fuel supply system wear more quickly than on regular fuel. Certain parts may also overheat due to increased abrasion, resulting in jamming or breaking of working parts. Therefore, the use of ethanol in the diesel engine fuel supply system has not been widely studied. When using ethanol in the diesel engine fuel supply system, it is recommended to use a fuel injection pump with external lubrication or to apply a special layer of nanocomposite materials on the work surfaces of plungers in order to increase the durability of the operating systems (Ma, X. Q. 2004; Olt et al., 2011b). The aforesaid solutions have not been widely used in regular diesel engine fuel-supply systems. This may be due to the high cost of complex systems and special procedures. Without any special procedures and external lubrication, the work surfaces of plunger pairs are processed well enough to allow short-term operation on liquids with poor lubrication qualities. Earlier studies include no reference to the duration of plunger pair in the environment which lacks the conditions required for operation.

Test plan: this test examines the impact of 94.6% bioethanol on the precise working components of diesel supply equipment. The test was performed with regard to the condition of the subsystems of fuel supply system and the wear of details thereof in the laboratory, based on practical tests and by using common test methods. Fuel injection pump УТН-5A with injectors 6T2 was selected as the fuel-supply system equipment to be tested. Selection of the devices to be tested was based on their use in most common fuel-supply systems. Laboratory tasks were divided as follows: 1) measurement of initial parameters of the details (Figure 3.1) and adjustment of the devices to be tested according to the factory requirements; 2) performance of durability test; 3) measurement of final parameters of equipment and details. Measurement methods are based on the standards specially developed by research institutions for the devices and details used in this article in view of their particular type of wear (Baširov, et al. 1978; Olt et al., 2011b).

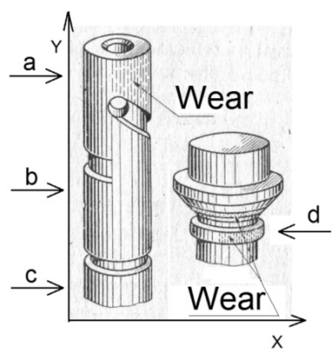

Figure 3.1. Measurement methods for fuel injection pump details (Baširov et al., 1978; Olt et al., 2011b)

In order to evaluate the condition of the details of a fuel injection pump, the compliance of operational parameters of plungers and delivery valves (hydraulic density) with factory requirements was measured both before and after the main test. Test stand KI-759 was used for measuring the hydraulic density of plunger pairs. In the course of measurement, the hydraulic density of plunger pairs was evaluated, which characterises the compliance of details with factory standards upon assembly of the pump.

In order to test fuel-supply system equipment, the authors decided that the main test should utilise a short-term operation method, during which the impact of fuel on the subsystems and work parameters of fuel-supply equipment was evaluated. According to the reference materials, the duration of the short-term operation method is 50 hours with interim section capacity measurements carried out in every 10 hours (Baširov et al. 1978; Olt et al., 2011b). The duration of our main test was 100 hours with interim measurements performed in every 10 hours. Interim measurements were required for checking the stability of the work parameters studied when testing the equipment. A test device was built for performing the test, based on fuel-injection pump test bench SDTA-1 and additional devices. Using additional devices on the aforesaid fuel-injection pump test bench was necessary for several reasons: to prevent the impact of fuel (ethanol) on the test stand and to reduce the quantity of fuel used for the test. When preparing the test stand for the main test, it was equipped with the following accessories: fuel container; fine filter; cooling device; fuel pipes; and thermometer (Figure 3.2).

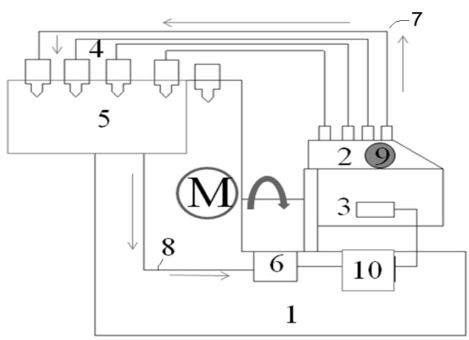

Figure 3.2. The scheme of the test principle: 1 – stand, 2 – fuel injection pump, 3 – fuel pre-supply pump, 4 – injector, 5 – fuel container, 6 – cooling system, 7 – fuel injection pipes, 8 – fuel pre-supply pipes, 9 – thermometer, 10 – fine filter (Olt et al., 2011b).

Developing method and flexible-fuel supply system based on wearing test results. Test results are shown in the chapter Results. Development of an additional fuel supply system (Ilves et al., 2012) requires examination of the problems that emerge when using liquid biofuels and it is also necessary to set the requirements for creating an innovative fuel supply system (Pahl et al., 2007; Ilves et al., 2012). The two types of biofuels to be studied include plant oils and bioethanol (max 96.6%). The aforesaid fuels should be usable in spark ignition engines and compression-ignition engines. The formation of air-fuel mixture by using a single fuel supply system is a complicated process, because in case of plant oils, great pressure is needed for injection in order to ensure sufficient fuel quantity and formation of high-quality air-fuel mixture in the cylinder (Puhan et al., 2009; Ilves et al., 2012). This is due to great viscosity of plant oils, which at the temperature of 27°C exceeds $30\,m^2\,s^{-1}$ (Hossain et al., 2010; Ilves et al., 2012). Bioethanol has low viscosity (~ $2\ m^2\ s^{-1}$). Bioethanol can be injected by means of injectors with low-injection pressure and a large nozzle opening. At the same time, the lubricating properties of bioethanol are significantly worse than those of plant oils (Smith 2012). This may cause rapid wear and corrosion of the precise surface finish of the fuel supply systems intended for plant oils. Bioethanol does not mix with standard fuels and plant oils. Therefore they cannot be mixed inside the fuel supply system in order to avoid the return of layered fuel in the fuel tank. Based on these properties, the following requirements have been prepared for the fuel supply system that describe the properties of devices in demand and less common on the market: 1) can be used with several types of biofuels in one fuel supply system; 2) ensure production of high-quality air-fuel mixture; 3) fuel supply system can be used in spark ignition engines and compression-ignition engines; 4) ensure durability of the fuel supply system.

The most common biofuel-operated fuel supply systems on the market are either direct or indirect injection standard systems. They are generally intended for one type of biofuel. Pressurised fuel is forced through the injector to the inlet manifold or directly into the cylinder. Main components subject to wear and tear are the precise surfaces in injectors and fuel pumps (injector needles, CR injector return valves, plungers). Examples of some fuel supply systems adjusted for biofuels can be found in the patent documents EP2208879, US2008202471, WO2009106647, US20090145403, etc. (Ilves et al., 2012).

The additional fuel supply system was developed based on the generally recognized TRIZ methods (Fowlkes 2010; Ulrich et al., 1995; Ilves et al., 2012), which in this case consisted of the following main steps:

1) identification and definition of the problem;
2) searching for typical problem similar to the problem identified;

3) analysis of known solutions;
4) finding the best solution for the problem in need of solution.

The stages of developing the fuel supply system.

Concept realisation and construction of the test device (Ilves et al., 2012).

1. Carrying out preliminary study:
   1.1. Selection of injectors;
   1.2. Checking the injection methods, process modelling.
   1.3. Elaboration of the principle of system construction.
2. CAD modelling.
3. Preparation of 3D drawings.
4. Preparation of control programmes for CNC benches.
5. Technological mapping.
6. Processing of the details in CNC.

Study of the processes in the fuel supply system.
Preparation of a simplified test device.
1. Monitoring of processes and making conclusions.
2. Elaboration of enhanced test device

Study of the operation of improved fuel supply system.
1. Improving the construction of the test device.
2. Monitoring the operation process of the test device and making conclusions.
3. Elaboration of enhanced construction of prototype devices.

Designing the prototype device.
1. Preparation of improved prototype devices.
2. Testing and solving any problems that might arise.

3.3.2. Comparative tests for characterising bioethanol (LGBE) and ethanol (DLGE) in compression-ignition engine

Motor tests were performed (Küüt et al., 2012c) with the compression-ignition engine D-120 (Table 3.5; Figure 3.3) and test stand Dynas3 LI-250 (Table 3.6; Figure 3.4) and in the laboratory for testing engines in the Estonian University of Life Sciences. The choice of the test engine was based on its construction. This engine is air-cooled and enables to use an additional supply system and indicated pressure measuring devices. Indicated pressure was measured with the device AVL

Indimodul 621. Pressure was measured with a Kistler 701A-type sensor which was installed in the opening of the glowplugs of the engine. The results of the measurements were saved in the computer. The indicated pressure measuring device enabled to perform measurements quickly and precisely and to collect data to be processed in the computer. On the basis of the results, comparative graphs were created and changes in the combustion process upon use of different fuels were examined. An additional supply system was used to supply the engine with different ethanol fuels. The basic supply system was used to ignite the fuel mixture with ordinary fuel (diesel fuel) as the ignition properties of ethanol fuel mixtures are worse. The additional supply device was a carburettor that was connected between the inlet manifold and the air measurement system. By adjusting the capacity of the main nozzle of the carburettor, optimal ethanol fuel delivery amount, at which the work of the engine was still stable, was determined earlier and published by Olt et al., 2011c. The only stable point was carburettor screw position 2 (Figure 3.5) whose data was used in analyses.

Table 3.5. The parameters of D120 engine

Engine D120	Manufacturer's data
Number of cylinders	2
Cylinder diameter, mm	105
Piston stroke, mm	120
Volume, litre	2.08
Power, kW	18.4
Pressure ratio	16.5
Cooling system	air-cooled
Nominal rotational speed, rpm	1800
Maximum torque achieved between, rpm	1260–1400
Maximum rotational speed, rpm	1950
Minimal rotational speed, rpm	800–1050
Injection pressure, MPa	17±0,7
Specific fuel consumption, g $(kWh)^{-1}$	241+7
Weight, kg	272–295
Oil volume, l	6.5
Type of combustion chamber	direct injection
Fuelpump	inline type
Oil pressure (nominal rotational speed), bar	1.5–3.4
Oil pressure (minimal rotational speed), bar	0.8
Fuel consumptions, kg h^{-1}	6.37
Volume per stroke per cylinder, mm^3 $cykl^{-1}$	59 ± 2
Fuel injection angle α_{pn}, deg	22…24° BTDC

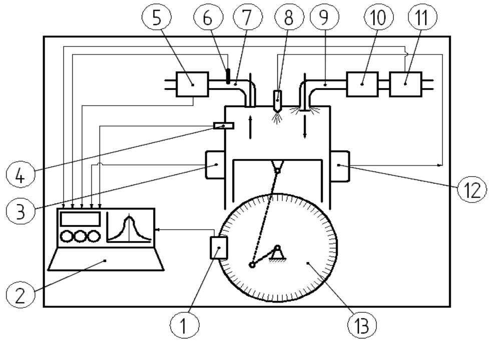

Figure 3.3. Diesel engine D-120 and the placement of its measurement and auxiliary devices: 1 – the sensor of crankshaft movement angle and sensor of rotational speed; 2 – engine remote control with AVL Indimodul device; 3 – engine unit for pressure and temperature sensors; 4 – pressure sensor Kissler 701A; 5 – opacimeter BAE 350-FIN; 6 – exhaust gases temperature sensor; 7 – exhaust manifold; 8 – regular fuel injector; 9 – inlet manifold; 10 – biofuel carburettor; 11 – air consumption meter SuperFlow 6-1490; 12 – diesel fuel supply equipment with control system Horiba ATS LFM 2003; 13 – graduated scale (Olt et al., 2011e).

Table 3.6. The producer's data of Engine test stand Dynas3 LI250 manufactured by Schenck GmbH

Dynas3 LI250	Manufacturer's data
Nominal power P_n, kW	250
Nominal intensity I_n, A	390
Nominal speed n_n, min^{-1}	4980
Torque at maximum nominal speed M_n, N·m	480
Maximum speed n_{max}, rpm	10000
Weight, kg	740
Nois up to 2 000 rpm without blower at 1m, dB	81
Cooling-air requirement, m^3 h^{-1}	900
Torque and Speed Asquisition	
Measuring range, torque M_{max}, N·m	650
Mechanical torque limit	5 x M_{max} of the AC induction motor
Max. accuracy, torque %	<± 0.1 related to full scale M_{max}
Temperature drift torque measurement, %	± 0.1/10K related to full scale M_{max}
Max. measuring accuracy, speed, rpm	± 1, for frequency content lower than 10Hz
System deviation, torque*, %	<± 0.17related to full scale M_{max}, for frequency content lower than 1Hz
System deviation, speed*, %	± 1. Max 0.25 ‰ related to full scale n_{max}, for frequency content smaller than 1Hz

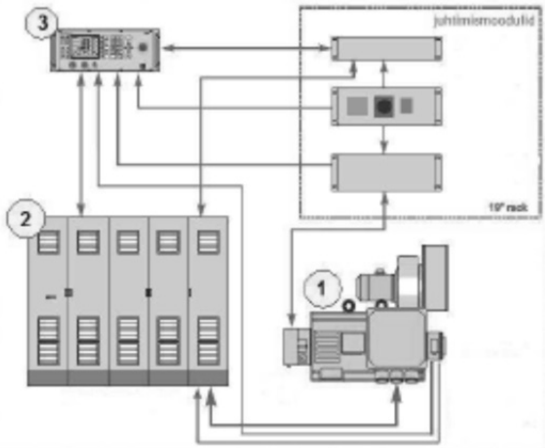

Figure 3.4. Block schema of the engine test bench Dynas3 LI250: 1 – AC induction motor with torque and speed acquisition, 2 – variable frequency drive, 3 – test bench controller (Olt et al., 2009a).

Motor tests on load characteristics' modes were performed $n_{e,T1}$ = 1300 min-1 and $n_{e,T2}$ = 1800 min-1. Fuel consumption B_f, air consumption B_a, exhaust gas temperature t_{egt}, temperature of motor oil t_o and the composition of exhaust gas were measured. The choice of measurement points of the motor test was partly based on the exhaust gas measurement standard ISO 8178 (ISO, 2006). As the amount of farmstead ethanol was limited, a partial measurement cycle was carried out. At the maximum load mode of the engine, some instability was observed. The measurements were carried out at load modes T1 and T2, $T_{e,T1}$ = 112 N·m and $T_{e,T2}$ = 92 N·m, respectively.

Measurements of fuel consumption were performed for diesel fuel consumed at a separate pilot injection and for the ethanol fuel consumption in the engine with an additional supply system. The measurement results were registered with electronic scales. Fuel consumption per hour B_{fet} and B_{fdk} was calculated (Formula 1.24) on the basis of the measured test results (Figure 3.5). Also special consumption b_e, was calculated (Formula 1.23) and a comparative analysis was performed.

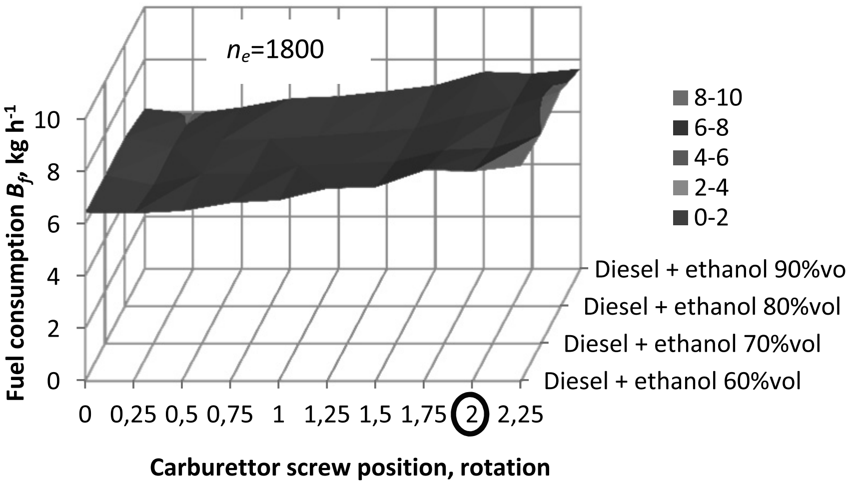

Figure 3.5. Diesel engine *D-120* fuel consumption

In order to compare differences in the engine output parameters, a fuel mixture was used as a test fuel which had been prepared on the basis of standard ethanol diesel fuel. In order to obtain clear differences in the test results, low-quality fuels were used (with high water content). One of the ethanol fuels was 97% ethanol diluted with water down to 60% (DLGE) and the other fuel was LGBE (farmstead ethanol 58.9% vol.). LGBE was prepared from lignocellulosic material in the fuel laboratory of the Estonian University of Life Sciences (Table 3.1).

Measuring device Bosch BEA 350 was used for measuring the exhaust gas composition. Exhaust gases were analysed for carbon dioxide (CO_2), carbon oxide (CO), hydrocarbon (HC), nitrogen oxides (NOx) and oxygen (O_2). In addition, the device enabled to measure the temperature of motor oil, crankshaft rotational speed and excess-air ratio (λ). On the basis of the measurement results, a comparative analysis was performed on the quantities of dangerous substances contained in exhaust gases by fuel.

3.3.3. Comparative tests for characterising bioethanol (LGBE-III) and ethanol (DLGE) in spark-ignition engine

The tests were performed (Küüt et al., 2011) by using gasoline 95 (regular fuel), ethanol (96.3%) and aforesaid LGBE-III (94.5%) as the fuel. In order to determine the dynamic and economic parameters of the engine at different modes (load and speed modes), diagrams based on experimental data were used (characteristics). Using the speed characteristic allowed to describe the relation between the parameters related to engine power and economy (net power P_e, hourly fuel consumption B_f, specific fuel consumption b_e, torque T_e) depending on crankshaft rotational speed nm. Audi A4 (OTTO) engine was used as the test engine (Table 3.7). In order to enable the test engine to work on bioethanol fuels, a Flexi Tune Sequential bioethanol device was connected to the electronic engine control system circuit between the engine control unit (ECU) and injectors (FlexiTune AutoX4, 2009). A bioethanol device was also connected to the λ-sensor. An attached bioethanol device allows using petrol, ethanol and their mixture in any ratio as fuel. The bioethanol device uses longer exposure of electronically controlled injectors to compensate the lower energetic value of ethanol.

Table 3.7. The producer's data of Audi A4 ADR engine (Autorevue, 1997; Küüt et al., 2011)

Audi A4 ADR	Manufacturer's data
Number of cylinders	4
Cylinder position	in-line engine
Cubic capacity, cm^3	1781
Bore, mm	81
Stroke, mm	89.4
Pressure ratio	10.3
Valves per cylinder	5
Timing mechanism	DOHC
Nominal power, kW	92
Nominal speed, min^{-1}	5800
Maximum torque, Nm	173
Rotational speed in case of maximum torque, min^{-1}	3950
Fuel consumption, $l\ (100\ km)^{-1}$	7.8
Ignition system	Motronic 3.2/Map-DIS
Injection system	Motronic 3.2/MFI-s
Supply system pressure, bar	4

According to manufacturer's data, the maximum torque of Audi A4 is 173 N•m, at 3950 min^{-1}. At the aforesaid crankshaft rotational speed, the choke position was 34% when not loaded. Choke position 34% was thus selected as one of the test modes. In order to obtain partial speed characteristics, the following test was performed with every test fuel: constant choke position at 34%; crankshaft rotational speed was changed by braking engine at fixed intervals n_e = 1350...3950 min^{-1}.

In the course of the tests, the engine load was increased until the crankshaft rotational speed decreased to the limit where the engine was still running steadily. The following parameters were measured at ten different crankshaft rotation speeds: torque T_e, fuel consumption m_f, test duration τ_d, air pressure p_{env}, air humidity φ_{env}, air temperature t_{env}, temperature of exhaust gases t_{egt}, position of injectors τ_i, ignition timing advance α_i, air consumption V_a, temperature of cooling liquid t_w. The information obtained was used for calculating the following parameters (Merker et al., 2012): net power P_e, hourly fuel consumption B_f, actual air consumption B_a, specific fuel consumption b_e, engine power efficiency η_e, effective pressure p_{me}.

3.3.4. Preparing the calculational price model (DLGE)

The production cost of machine works in agriculture is calculated (Küüt et al., 2012a) according to the costs per field area unit. Direct expenses on a certain field area unit C_F, which takes into account the productivity of aggregate (W), depreciation (a_T, a_M), technical maintenance and repairs (p_T, p_M), fuels and lubricants, and wages (c_w), are expressed as follows (Reintam, 1982):

$$C_F = \frac{1}{W}\left[\frac{B_T(a_T + p_T)}{100T_T} + \frac{B_M(a_M + p_M)}{100T_M} + \frac{b_e v_p R_x c_f}{\eta_T \xi} + c_w\right], \qquad 3.3$$

where the component of the formula

$$\frac{b_e v_p R_x c_f}{\eta_T \xi}, \qquad 3.4$$

describes the expenditure on fuel and lubricants during one working hour and it can therefore be referred to as the hourly cost of fuel consumption C_f (€ h^{-1}). An important parameter in determining the hourly cost of fuel consumption is the fuel sales price c_f, i.e. fuel price in filling station (€ kg^{-1}).

Considering the work resistance of agricultural vehicle R_x and $R_x/(\eta_T\xi) = F_h$, where F_h is the drawbar pull, and knowing that power P is the product of force F and velocity v, we can express the driving power of the tractor P_h as follows:

$$P_h = \frac{R_x v_p}{\eta_T \xi}, \tag{3.5}$$

where v_p – working speed of the agricultural vehicle;

η_T – driving efficiency of the tractor;

ξ –nominal driving force efficiency of the tractor.

Thus we can express the relation (3.4 and 3.5) as follows:

$$C_f = \frac{b_e v_p R_x c_f}{\eta_T \xi} = b_e P_h c_f, \tag{3.6}$$

where b_e – specific fuel consumption (kg kJ^{-1}).

Relation (3.6) indicates that product b_eP_h expresses hourly fuel consumption B_f, thus we can bring forward the following relation between hourly cost of fuel consumption C_f and fuel sales price c_f (€ kg^{-1}):

$$C_f = B_f c_f, \tag{3.7}$$

where B_f – hourly fuel consumption (kg h^{-1}).

The hourly fuel consumption cost and its changes depending on bioethanol quality is a topic of interest within this thesis.

Calculation model was prepared on the basis of the cost price of bioethanol production and bioethanol limit price generated in the course of use. Thus the model has two sides or characteristics (two regression equations). In the first case, the cost of fuel consumption is determined according to the ethanol content, followed by a calculation of the limit price of bioethanol fuel. In the second case, bioethanol price generated in the course of fuel production is found, depending on the ethanol content and production method. The model allows the determination of optimum ethanol content, in which case the production and use of bioethanol is considered economically reasonable in comparison with regular fuel. The relation between the highest given production price of bioethanol (limit price, when used) and the actual production price of bioethanol can be presented as follows:

$$\Delta c_f = c_{fet} - c_{fetp}, \quad 3.8$$

where c_{fet} – bioethanol limit price;

c_{fetp} – bioethanol production price, depending on ethanol content.

Description of Production Process and Price Formation of Bioethanol (LGBE).

The second part of the model describes the formation of the production price of c_{fetp} LGBE depending on the ethanol content. The first distillation resulted in 10..12% ethanol content, the second distillation resulted in ca 50…60% and the third in ca 90% ethanol content, which allowed calculating the product prices for three different ethanol contents (€ kg^{-1}). Researching the cost of production c_{fetp} dependence of ethanol concentration et by interpolation (Stewart, 2009), we obtain the following function:

$$c_{fetp} = Ue^{Va_c}, \quad 3.9$$

where a_c – ethanol content;

U; V – parameters of exponential distribution.

Figure 3.6 shows the relative values of the formation of the production price of LGBE made of lignocellulose mass. In the analysis of production price, the price of 90% LGBE is equal to 100% relative value. In this case it was reasonable to present the result in relative values, because the actual production price values were too high for using testing technology (testing equipment) for large-scale bioethanol production. The quantities used in experimental LGBE production were small and thus the effect generated by increasing the production capacity was not taken into account when calculating the production price.

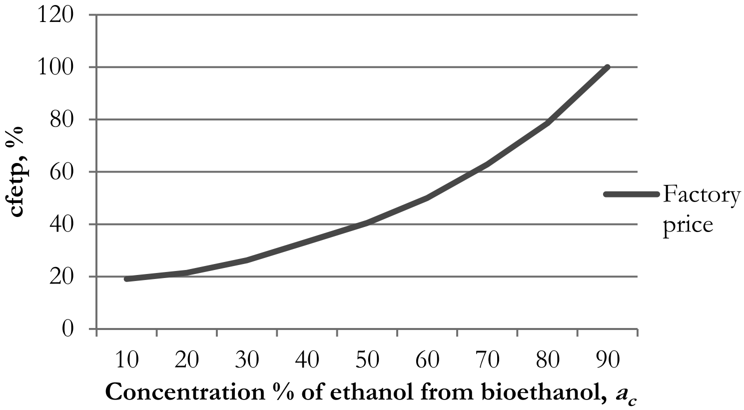

Figure 3.6. Cost price formation of LGBE made of lignocelluloses in the Fuel Laboratory of the Estonian University of Life Sciences, depending on ethanol content (Küüt et al., 2012a).

When studying the use and production of LGBE as a complex solution, we are first and foremost interested in the part of the characteristic in the graph area referring to 60…90% ethanol content (Figure 3.7). This area can be characterised by using linear regression model:

$$c_{fetp} = Ua_c + V\,, \tag{3.10}$$

where U, V – regression coefficients (initial ordinate and slope);
a_c – ethanol content value 60…90%.

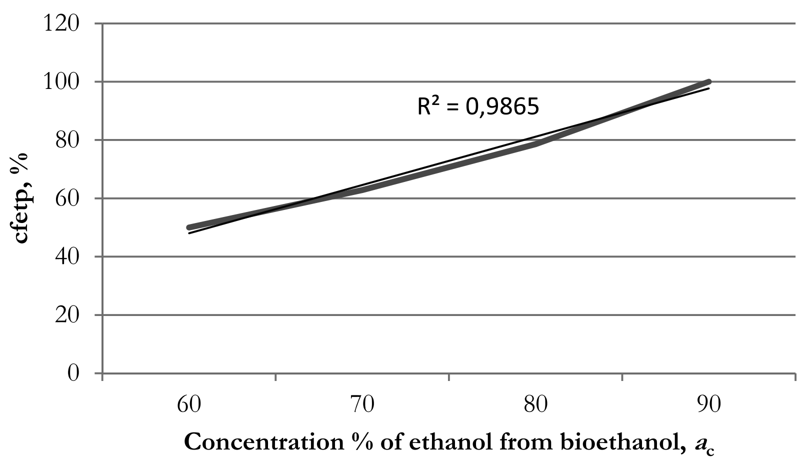

Figure 3.7. Cost price formation of LGBE made of lignocelluloses in the Fuel Laboratory of the Estonian University of Life Sciences, depending on ethanol content (Küüt et al., 2012a).

Model of Bioethanol (DLGE) Price Formula while Using in Compression-Ignition Internal Combustion Engine

The first part of the model c_{fet} enables to estimate the highest limit price of bioethanol fuel in comparison with regular fuel price, provided that the cost of bioethanol fuel consumption C_{fbio} is lower than the cost of regular fuel C_{freg} used for performing the same amount of work. Additionally, it is possible to assess the variation in the required amount of fuel upon partial or full-scale introduction of bioethanol fuel. DLGE has been used in this study to investigate bioethanol limit price.

In order to maintain or reduce the price of the product or service, the relation (3.11) is expressed through the following relation when using the cost of fuel used in tests:

$$C_{fbio} \leq C_{freg}, \tag{3.11}$$

If more than one type of fuel is simultaneously used in the engine, the cost of fuel consumption is expressed as follows (3.12):

$$C_f = C_{fdk} + C_{fet}, \tag{3.12}$$

where C_{fdk} – cost of diesel fuel consumption, € h^{-1} and

C_{fet} – cost of DLGE consumption, € h^{-1}.

In this study a bi-fuel supply system (on diesel engine) has been used to supply the engine with fuel, which—in view of formulas (3.7) and (3.11)—leads to the following:

$$B_{fdT1}c_{fdT1} \geq B_{fdT2...T5}c_{fdT2} + B_{fetT2...T5}c_{fetT2...T5}, \tag{3.13}$$

where B_{fdT1} – diesel fuel consumption in regular test, kg h^{-1};

$B_{fdT2...T5}$ – diesel fuel consumption in case of bi-fuel supply system, kg h^{-1};

$B_{fetT2...T5}$ – DLGE consumption in case of bi-fuel supply system, kg h^{-1};

c_{fdT1} – dieselfuel price in regular test, € kg^{-1};

$c_{fdT2...T5}$ – diesel fuel price in case of bi-fuel supply system, € kg^{-1};

$c_{ftT2...T5}$ – DLGE price in case of bi-fuel supply system, € kg^{-1}.

Given limit price for using or producing bioethanol in comparison with using regular fuel is shown in formula (3.14).

$$c_{fetT2...T5} \leq \frac{B_{fdT1}.c_{fdT1} - B_{fdT2...T5}c_{fdT2...T5}}{B_{fetT2...T5}} \qquad 3.14$$

If diesel fuel at the same price is used for both tests $c_{fd} = c_{fdT1} = c_{fdT2...T5}$ (€ kg^{-1}), then $c_{fdT2...T5}$ can be written down as follows:

$$c_{fetT2...T5} \leq \frac{(B_{fdT1} - B_{fdT2...T5})c_{fd}}{B_{fetT2...T5}}. \qquad 3.15$$

3.3.5. Determining measurement uncertainty in engine tests

The measurement uncertainty has been calculated to evaluate the precision of measurements on diesel engine tests. It is generally assumed that the measurement result is the best representation of the measured size. Measurement uncertainty describes the scepticism of the measurement results due to the random nature of measurements.

The standard EA-4/16 has been used as the base document for calculating cumulative uncertainty of measurement results. Type A evaluation method is the statistical analysis of repeated measurements during the testing. Type A uncertainty is experimental standard deviation. (Laaneots et al., 2002 & 2012)

In the case of type B evaluation, the source information originates from somewhere else, it evaluated on the basis of experience, theory or some other principle, taking into account the distribution of probability.

Cumulative uncertainty U consists of cumulative uncertainty u_A based on statistical methods (type A standard uncertainty) and cumulative uncertainty u_B based on other sources (type B uncertainty) and it can be calculated according to the following formula:

$$U = \sqrt{U_A^2 + U_B^2} \qquad 3.16$$

The generally known formula for finding measurement uncertainty U_A is:

$$U_A = \sqrt{\frac{1}{n(n-1)} \sum (x_i - \bar{x})^2} \qquad 3.17$$

Where n is the number of repetitions and

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i , \qquad 3.18$$

is the average value of the sample group.

The components of measurement uncertainty U_B are usually the measurement uncertainty u_{et} of calibration data about reference models or measuring instruments—this value is based on the extended measurement uncertainty u given by the verifier or model's limits of error Δ_{max} upon verification. The value of these will be changed to the level of standard uncertainty, i.e. k_U=1. If it is presumed that the distribution of uncertainty is even within the allowed limits of uncertainty (hereinafter this is presumed), then the change to standard uncertainty shall proceed according to the formula:

$$u_{et} = \frac{\Delta_{\max}}{\sqrt{n}} \qquad 3.19$$

Intermediate tests were performed with diesel fuel to compare the measurements of ethanol at various concentrations. The measurements were performed with the engine test stand. The results of three different tests were used for determining measurement uncertainty. The load and environmental conditions remained constant while the test was performed.

Used measurement instruments:
Test bench *Dynas3 L250*
Bench's control unit *SCHENCK*
Weighting device *CAS CI 2001A*
Stopwatch

4. RESULTS AND DISCUSSION

4.1. Impact of ethanol on the fuel injection pump of a diesel engine

The test results (Olt et al., 2011b) reveal that when using the stand liquid and ethanol in the fuel injection pump, there was no significant change in the section capacity, irrespective of the differences in the density and viscosity of diesel fuel and ethanol. This leads to the conclusion that the fuel injection pump does not need a separate section capacity adjustment when using ethanol. In order to compensate the difference in the calorific value of the fuel compared to using diesel fuel in the engine, it is possible to increase the section capacity. After the first ten-hour test cycle, the capacity of the first and fourth section was reduced by 6 cm^3. The reduction of section capacity was caused by the shifting that occurred between the case and control rack when running in the fuel injection pump. No significant reduction of section capacity was observed in the course of further test cycles, as seen in Figure 4.1.

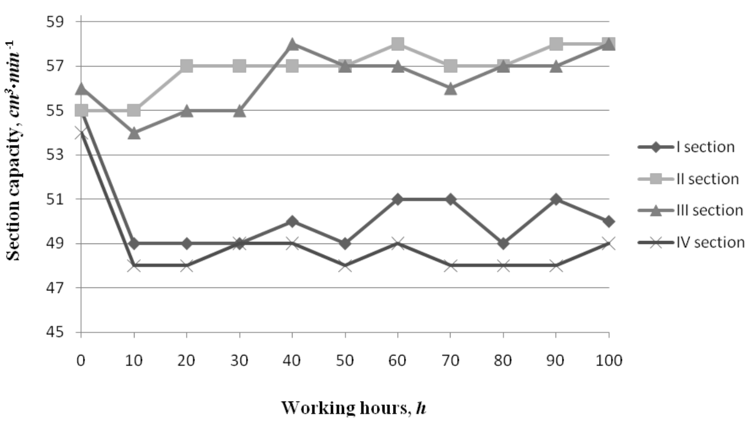

Figure 4.1. The section capacity of an injection pump depending on test time (Olt et al., 2011b).

We may conclude that the operation of valves in ethanol environment during 100 work hours does not cause significant wear that would lead to major changes in the capacity of fuel supply equipment. The same can be said in describing the wear of plunger pairs. The greatest change in deflection, 1.667 µm, was found in the fourth plunger. The results gained from measurement of the hydraulic density of plunger pairs did not differ from the initial measurements, and the results corresponded to the factory requirements. Under the microscope one can barely see noticeable scratches on the surface of the plunger. More visible scratches of work surface, however, are seen on the delivery valve retraction collars (Figure 4.2), which, according to the measurement results, did not change the hydraulic density according to the factory requirements.

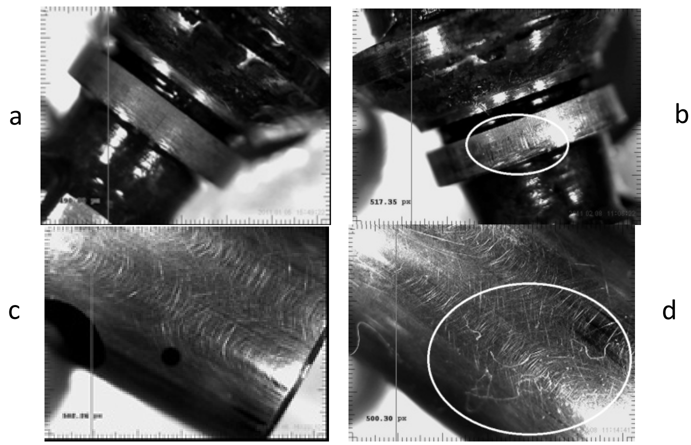

Figure 4.2. Work surface of the subsystem: a – unloading collar before testing; b – unloading collar after testing; c – pump plunger before testing; d – pump plunger after testing (Olt et al., 2011b).

The main problem when using ethanol in the fuel-injection pump was the possible contact of ethanol with lubricant oil. The problem consists in the non-solubility of ethanol and oil, which may cause serious issues in centrally oiled engines with this type of fuel injection pumps. Another problem arises from the corrosion emerging during the storage of the pump, as it causes damage to the work surfaces of moving details.

4.2. Power and economic parameters for comparing ethanol (DLGE) and bioethanol (LGBE) in compression-ignition engine

This chapter presents the results of the comparison of power and economic parameters (Küüt et al., 2012c) to describe the differences according to the content of LGBE residues (production method). The test conditions and used fuels have been described in chapter 3.2.2.
Measurements were performed with all three fuels at a similar load and speed modes. It appeared that with crankshaft rotational speed $n_{e,T1}$ =

1300 min^{-1}, consumption of ethanol fuel mixture per hour B_{fet} was higher by 8.34% than that of farmstead ethanol (LGBE) fuel mixture (Figure 4.3). Consequently, with ethanol (DLGE) fuel mixture specific fuel consumption b_e was higher by 4.87% compared to LGBE. No significant differences in economy-related parameters of ethanol fuels (fuel consumption) were observed upon performing measurements at the crankshaft rotational speed $n_{e,T2}$ = 1800 min^{-1} (Figure 4.4)

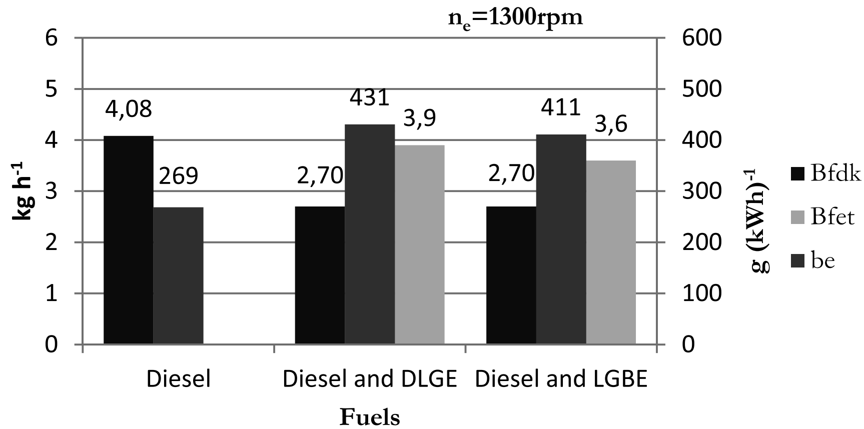

Figure 4.3. Comparison of fuel consumption and specific fuel consumption with tested fuels at the crankshaft rotational speed of 1300 rpm (Küüt et al., 2012c).

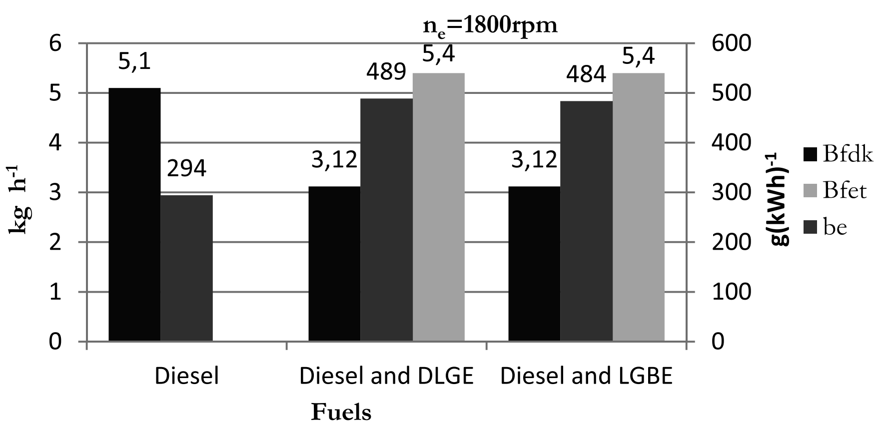

Figure 4.4. Comparison of fuel consumption and specific fuel consumption with tested fuels at the crankshaft rotational speed of 1800 rpm (Küüt et al., 2012c).

Differences were observed while comparing ethanol fuel mixtures and diesel fuel at higher load modes. At the crankshaft rotational speed $n_{e,T1}$ = 1300 min^{-1} the special consumption of DLGE fuel mixture was higher by 37.6% compared to diesel fuel, the special consumption of LGBE fuel mixture was higher by 34.5%. At the crankshaft rotational speed $n_{e,T2}$ = 1800 min^{-1}, the special consumption of DLGE and LGBE fuel mixture was comparatively similar. Compared to the use of diesel fuel, DLGE fuel mixtures had a 60% higher special consumption (Figure 4.4), which is due to a considerably lower calorific value Q_{HV} of ethanol. Study of the capacity and economy-related parameters of the engine showed that the residues contained in LGBE had energetic value and the effect may vary depending on their amount. In the framework of the present study which showed a minimal share of residues in LGBE, the effect on the capacity and economy-related output parameters of the engine was not high compared to the use of DLGE. Ethanol diluted with water can be used for studying the use of ethanol fuels with a considerably smaller amount of residues in different engines in order to assess the capacity and economy-related parameters of engine.

Description of the combustion process. Figures 4.5 and 4.6 display graphs with engine indicated pressure values with respect to crankshaft movement angle. Fifty measurement cycles in each measurement point and calculated mean values have been taken as the basis for drawing the graphs. The results obtained in test T1 do not show significant differences between the use of DLGE and LGBE; the same cannot be said about test T2. In case of test T2, with the use of DLGE fuel, the maximum value of indicated pressure in combustion process is lower by 5 bars than with the use of LGBE (Figure 4.6), which also explains an increase in the special consumption of fuel b_e in case of an ethanol fuel mixture compared to LGBE.

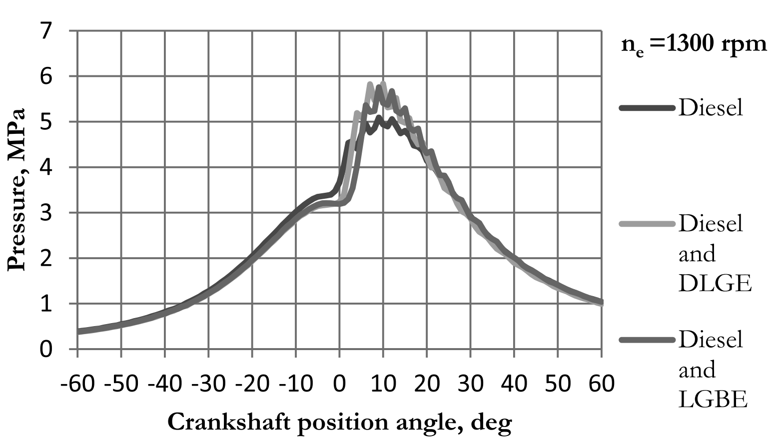

Figure 4.5. Test T1 comparative diagram of indicated pressure (Küüt et al., 2012c).

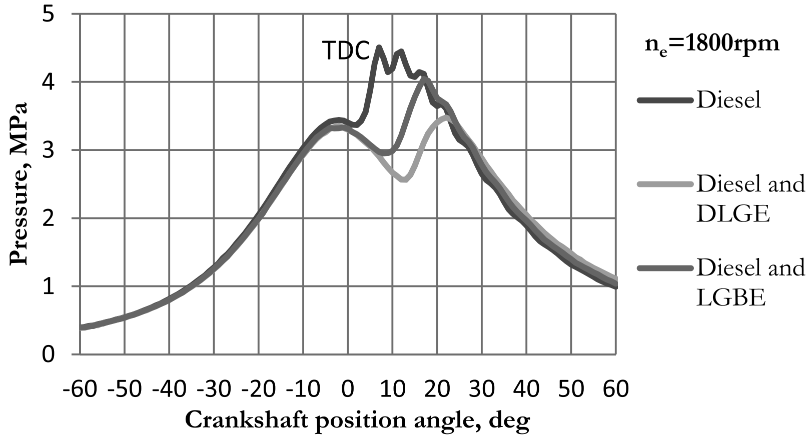

Figure 4.6. Test T2 comparative diagram of indicated pressure (Küüt et al., 2012c).

Analysis of the exhaust gases. Comparison of the results of the analyses of exhaust gases shows no significant differences in the use of DLGE and LGBE (Figure 4.7). Exhaust gases were tested for CH, NOx, CO and $CO_{2.}$ Differences in the amount of CH and NO_x were observed in the use of diesel and ethanol fuels (Figure 6.6), which is subject to the temperature of combustion process. According to the measurement results, the temperature of exhaust gases in the outlet manifold was higher by 90º C with test T1 and 60º C with test T2 when diesel fuel was used compared to the use of ethanol fuels. As the temperature of exhaust gases increased, the share of hydrocarbons decreased and that of nitrous oxides increased significantly, which is functionally related to an increase in the combustion temperature (Pulkrabek, 1997). According to test T1 results, NO_x has decreased by 27% with DLGE fuels and 40% with LGBE fuel as compared to the use of diesel fuel. In test T2, NO_x values have decreased by 52% with DLGE and 51% with LGBE. The share of HC in exhaust gases has increased as compared to diesel fuel, which is related to incomplete combustion, especially with test T2 (Figure 4.6; 4.8). The results of analyses of the components of exhaust gases of fuels containing ethanol are quite similar, which is due to minor differences in the level of residues (Table 3.1).

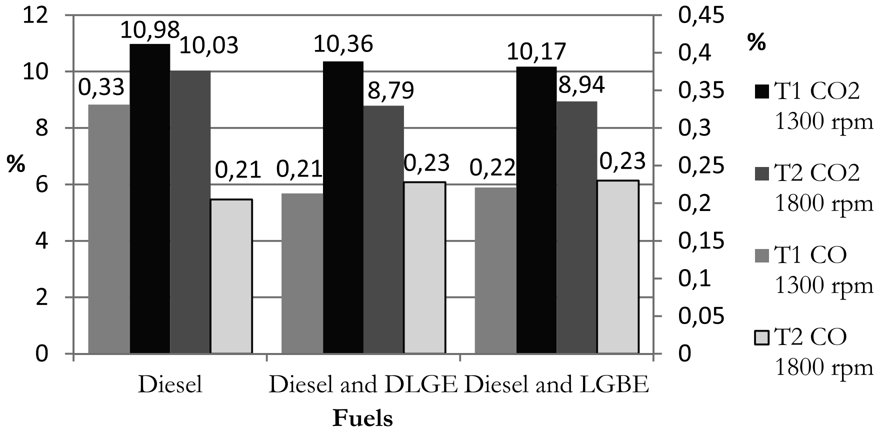

Figure 4.7. Comparison of the amounts of CO and CO_2 contained in exhaust gases with tests T1 and T2 (Küüt et al., 2012c).

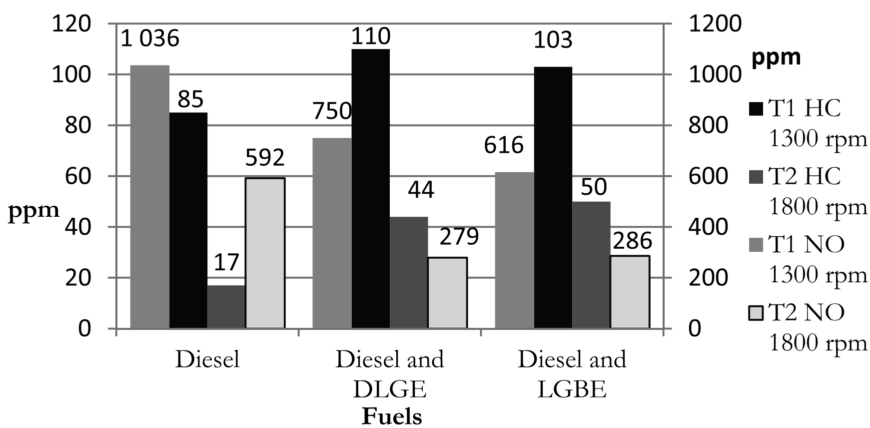

Figure 4.8. Comparison of the amounts of HC and NOx contained in exhaust gases with tests T1 and T2 (Küüt et al., 2012c).

The aim of the present study was to examine the effect of fuel with a lower absolute ethanol content on the output parameters of an engine that depended on residue (fusel oil) content in the fuel. The results of the test indicate that it is possible to use ethanol diluted with distilled water as motor fuel. As LGBE produced by us was produced using the classical method and the residue content was considerably low (0.05 g l^{-1}), there is no significant difference in the measured parameters. According to the obtained results, pilot tests for assessing the economy and capacity-related parameters of engine can be performed by using ethanol diluted with distilled water imitating farmstead ethanol. At the same time, determining and assessing the volume of exhaust gases requires the use of LGBE that needs to be used in the engine because of the differences revealed in the test results. Further studies on exhaust gases require supplementary studies on the use of LGBE as the impact of residues on exhaust gases and the environment is not known.

4.3. Power and economic parameters for comparing ethanol and bioethanol (LGBE-III) in spark-ignition engine

A comparative analysis prepared on the basis of the test results and calculations is given below (Küüt et al., 2011). The tests were performed by using gasoline 95 (regular fuel), ethanol (96.3%) and aforesaid farmstead ethanol (94.5%)—LGBE-III as a fuel. Figure 4.9 shows that gasoline has the highest and farmstead ethanol has the lowest torque in the entire diagram.

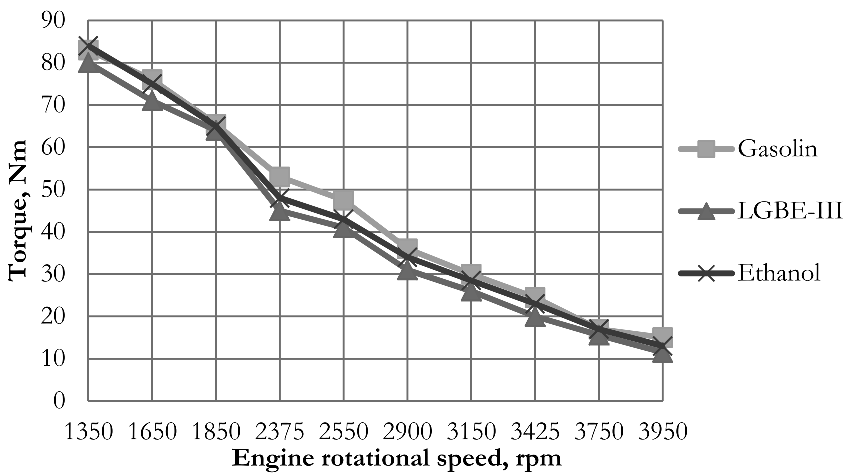

Figure 4.9. Torque T_e depending on the speed frequency of the engine n in case of different fuels (Küüt et al., 2011).

Average engine power in case of given fuels was approximately the same (Figure 4.10). Engine power was calculated by using the formula 2.6.

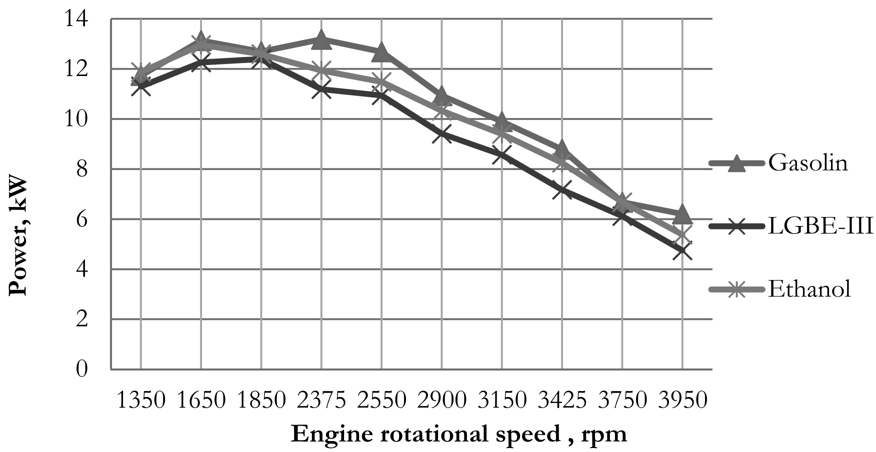

Figure 4.10. Power Pe depending on the speed frequency of the engine in case of different fuels (Küüt et al., 2011).

Based on the test results, the average values of studied parameters (f=average) are used to provide a better characterisation of the fuels within the entire partial speed characteristic range (n = 1350...3950 min^{-1}) and then expressed in percentage (Figure 4.11). While, in comparison with gasoline, the loss of power was approximately 5% in case of ethanol, that parameter was 11.2% lower in the case of farmstead ethanol.

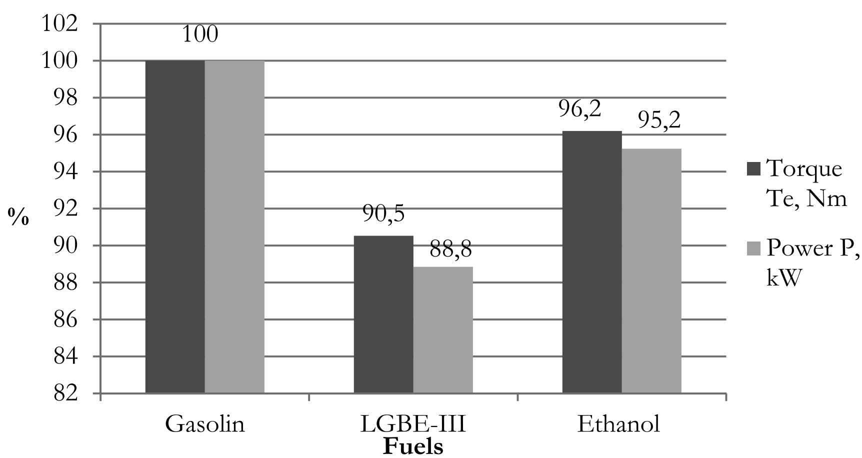

Figure 4.11. Ethanol fuels compared to gasoline (Küüt et al., 2011).

Main typical parameters in the analysis of fuel use and in making recommendations in terms of economical use thereof include specific fuel consumption and engine efficiency. Hourly fuel consumption B_f, measured on the stand (Figure 4.12) was used to calculate specific fuel consumption b_e, (Formula 2.13; 2.14).

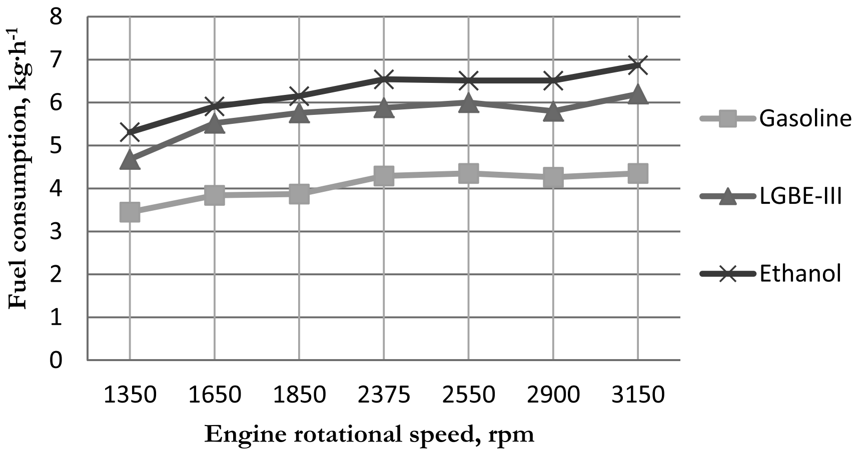

Figure 4.12. Fuel consumption B_f depending on the speed frequency of the engine in case of different fuels (Küüt et al., 2011).

Specific fuel consumption increased along with increased torque. Specific fuel consumption of farmstead bioethanol was on an average 58% higher than gasoline and that of regular ethanol was 62% higher (Figure 4.13).

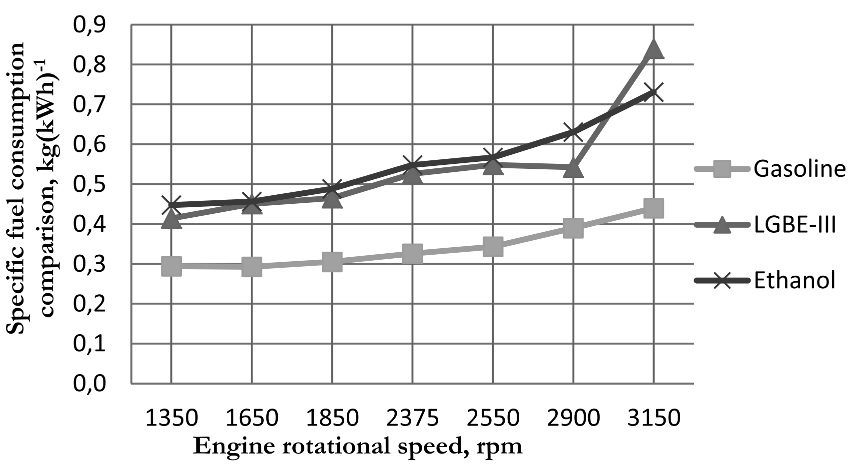

Figure 4.13. Specific fuel consumption b_s depending on the speed frequency of the engine (Küüt et al., 2011).

These results met the expectations, but they also gave rise to various questions. The engine operated steadily, and there were no major deviations from work parameters. Although farmstead ethanol has a lower ethanol content, its main additives include aldehydes (acetic acid, etc.), esters (formic acid ethyl ester, acetic acid methyl ester, acetic acid ethyl ester, etc.), methylated spirit, post-additives such as higher alcohols (fusel oils) and iso-butyric acid ethyl-, iso-valerian acid ethyl-, acetic acid-iso-amyl-, iso-valerian acid-iso-amyl esters with similar boiling point. The results gained upon testing ethanol and farmstead bioethanol were approximately the same, as seen from the diagrams. Meanwhile, engine efficiency was higher in the case of farmstead bioethanol, which took into account the power, specific fuel consumption and calorific value. The results led to the conclusion that it is necessary to carry out additional tests with bioethanol based fuels both in spark ignition and pressure ignition piston engines. For better characterisation of the bioethanol fuel it is necessary to constantly monitor the production process, which was lacking in this case. Therefore, it is intended to develop a small production process, which would allow constant monitoring of fuel properties, and modify them where necessary and provide economic assessment to the production.

4.4. The development of an additional fuel supply system to an internal combustion engine

The development of a new fuel supply system (Figure 4.14) requires the reduction of pressure inside the supply system and exact number of junctions (Ilves et al., 2012). At the same time one has to ensure the highest possible quality of air-fuel mixture in the cylinder. One alternative is to use fuel supply systems equipped with compressed air, where the air flow channelled through a venturi nozzle utilises underpressure to suck the fuel into the injector, where the air and fuel are then carburized. The advantage of this system is lack of precise surfaces and low pressure in the fuel supply system. In order to allow using the fuel supply system both in spark ignition and compression-ignition engines, it has been placed in the engine inlet manifold.

The fuel supply system has been developed on an experimental basis, i.e. an initial test device has been built and it has been improved and modified to solve the problems emerging in the course of testing.

Working principle and design of the fuel supply system

Air flow is drawn through injector 1, creating underpressure in the fuel supply line 3 at the end of the injector when passing through the jet opening. Due to underpressure, the fuel will be sucked through the fuel supply line into the injector, where the fuel is carburized. In casing 4 of the fuel supply system, the resulting air-fuel mixture is mixed with air again and drawn into the cylinder. Fuel inlet manifold has at least two injectors that ensure sufficient productivity of the fuel supply system at different engine modes. The function of fuel inlet regulator 2 is to adjust the quantity of fuel feed from the tank. Irrespective of the viscosity and density of fuel, the system allows breaking the fuel jet into small parts. Implementation of this concept into an engine fuel supply system represents a complex process.

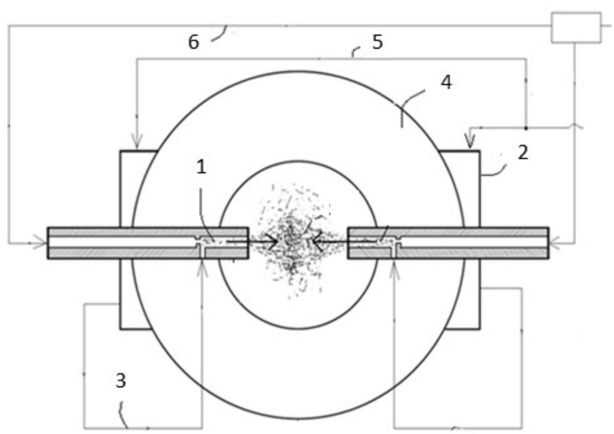

Figure 4.14. Basic scheme of the fuel supply system: 1 – injector; 2 - fuel inlet regulator; 3 – fuel supply line; 4 – casing; 5 – fuel supply line; 6 – compressed air (Patent EE 05665 B1, 2013).

Stage I: the aim is to find a suitable construction for implementing the concept of the fuel supply system. For that purpose the injection quality and productivity V_k of different injectors have been studied in biofuels with varying viscosity (Figure 4.15). Injectors are placed in the casing which is positioned in the inlet manifold of the engine. Problems found while testing include condensation of the injected fuel on casing walls and adjustment of fuel quantity. In order to reduce fuel condensation, it is necessary to adjust the quantity of injected fuel so as to ensure required engine performance without forming excess air-fuel mixture in the inlet manifold. Air flow regulator is used for adjusting the quantity of injected fuel.

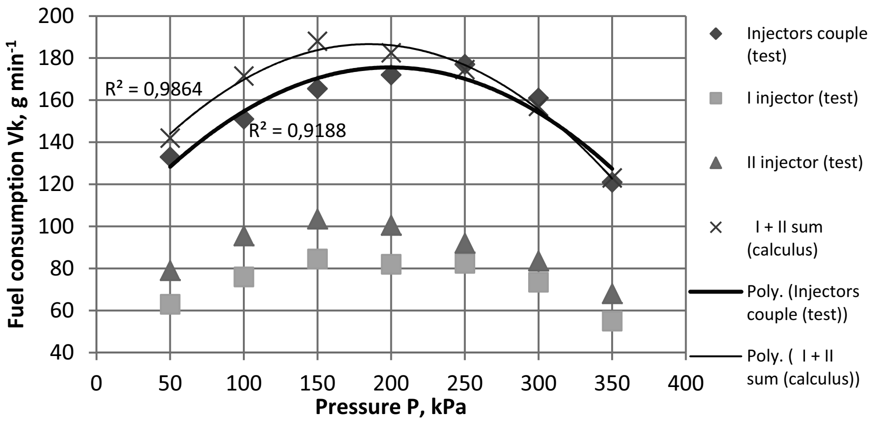

Figure 4.15. Example of the injection analysis

Stage II: engine testing revealed that the underpressure generated in the inlet manifold was high enough to force the fuel to flow to the manifold through the injectors. This results in uncontrollable engine operation, where the fuel flow to the cylinder increases along with the increasing rotational speed of the crankshaft. This problem can be solved by supplementing the system with a fuel doser that channels the fuel to the injectors. Doser consists of a fuel distributor, electromagnetic valve and control module. Doser must be placed as close to the injector as possible in order to reduce the impact of fuel in the fuel supply line during the work mode of the engine, when the doser is in a closed position. Dosing effect consists in the operation of pulse-modulated electro-magnetic valve at a fixed frequency by changing the signal fill factor. Air flow adjustment is not necessary in case of the above-mentioned solution.

Stage III: testing the fuel supply system equipped with an electronic fuel dosing system revealed excessive formation of air-fuel mixture in the inlet manifold. In order to remove the condensed air-fuel mixture from the system, the position of the system casing on the engine has been altered and a return line has been added which allows directing the condensed fuel back to the fuel tank.

Stage IV: prototype device has been designed in view of the fact that the fuel must flow out of the casing of the fuel supply system at various engine positions. The reason for that comes from the problem found when testing the device in a spark ignition engine. If the cylinder is filled with a too rich air-fuel mixture the combustion process will take a long time, which causes backfire in inlet manifold when opening the inlet valve. In case of backfire, the condensed fuel ignited in the inlet manifold. It is necessary to supplement the system with a lambda sensor to solve the problem, the signal of which provides a basis for controlling the air-fuel mixture preparation.

4.5. Preparing the calculational price model

The formula in the first part of the calculation model was used to determine relative bioethanol (DLGE) limit prices in case of different ethanol content (Figure 4.16) to describe the impact of bioethanol fuel on the D-120 engine. (Küüt et al., 2012a)

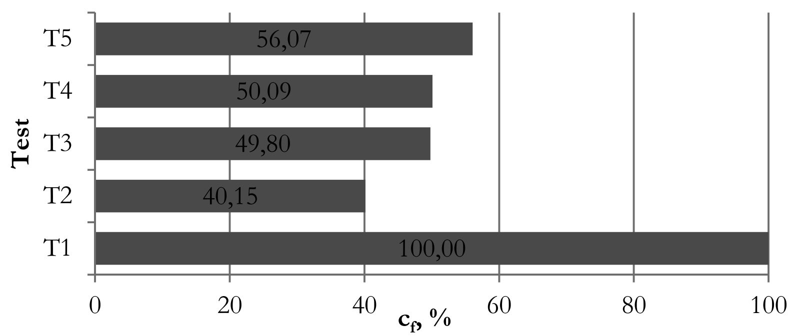

Figure 4.16. Relative limit prices of bioethanol in case of different ethanol content in comparison with diesel fuel (Küüt et al., 2012a).

Calculation and comparison of absolute limit prices is based on diesel fuel price $c_{fd} = 100\%$. When using 60% DLGE with diesel fuel, the production price must be ca 60% lower than that of diesel fuel. Meanwhile, when using 90% DLGE, limit price is ca 44% lower than that of diesel fuel. As a result of that, when substituting the 60% DLGE with 90% DLGE, one has to expect ca 40% increase in bioethanol production price. This can be used for ensuring competitive production price when choosing the method for LGBE production. One of the factors in calculating bioethanol limit price is the quantity of fuel consumed. Given the quantities of consumed fuel it is possible to calculate the required resources of raw material. Measured fuel quantities consumed in the course of described tests are shown in Figures 4.17 and 4.18.

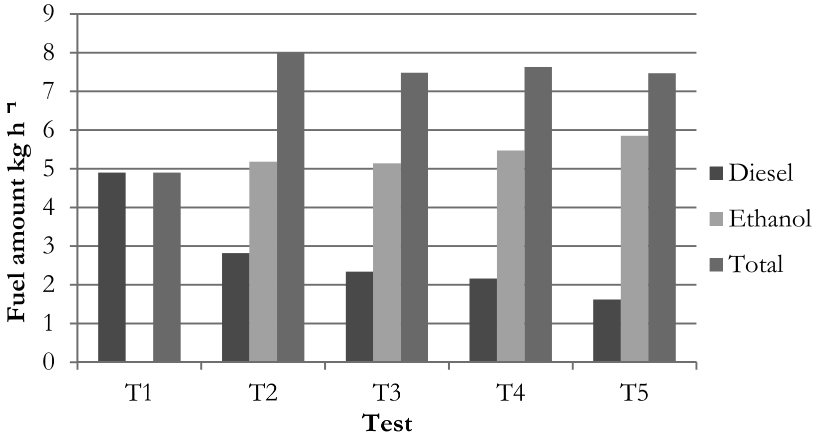

Figure 4.17. Absolute quantities of fuel used for testing when comparing diesel and DLGE (Küüt et al., 2012a).

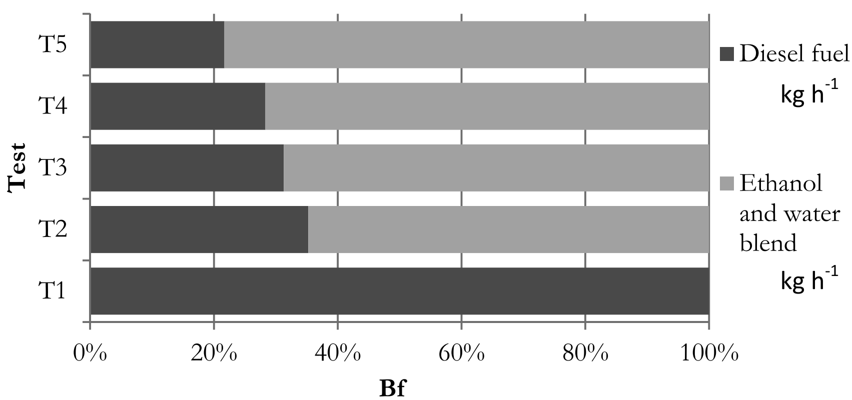

Figure 4.18. Relative proportion of fuel used for testing when comparing diesel and DLGE (Küüt et al., 2012a).

The relation between limit price of DLGE in *D-120* engine and our production price of LGBE was determined on the basis of calculation model. Figure 4.19 provides a graphical presentation of the change in case of lowering the ethanol content in bioethanol, i.e. when producing bioethanol at a lower quality. In this case we also have to consider the change in the proportion of diesel fuel (Figure 4.18), which affects the formation of bioethanol limit price. The calculation is different in case of a single fuel supply system (engine with high-tension ignition) and, therefore, not considered in this present study.

The graph (Figure 4.19) created on the basis of the model has in this case been prepared so that the relative production price of 90%

bioethanol and relative limit price are equal to 100%. Change in ethanol content causes alternating difference in price Δc_f. If the limit price for using low-content bioethanol (60%) drops by 28.4% in comparison to high-content bioethanol (90%), then the decrease in production price when using 50% is much bigger. Therefore, we may argue that the production of low-content bioethanol is reasonable under the conditions used in the study.

However, one has to take into account that when using low-content bioethanol, the engine with compression-ignition requires a larger quantity of diesel fuel. When using 90% bioethanol, the engine needs 21% of the total diesel fuel consumption, but when using 60% bioethanol it needs 36% of diesel fuel.

The production price of 60% LGBE is 30% lower than the limit price for using it in the engine, which means a lower cost of the fuel consumed, which in turn is seen in the specific cost per field area.

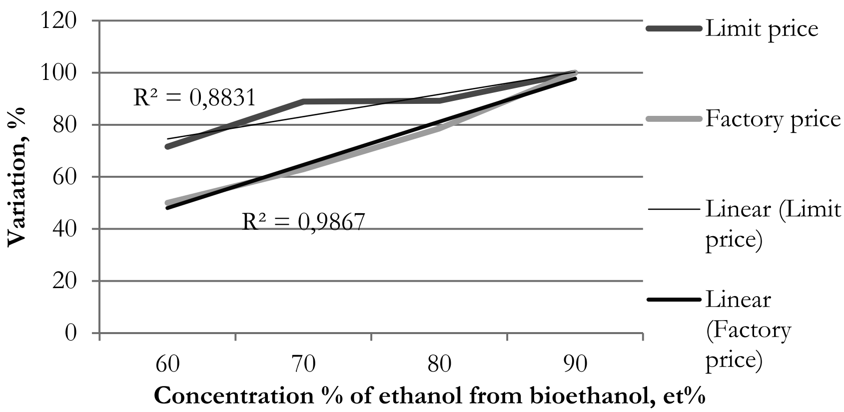

Figure 4.19. Comparative price formation of DLGE limit price and actual LGBE production price, depending on the ethanol content (Küüt et al., 2012a).

The drop ΔC_f in the cost of fuel consumption (€ h^{-1}) in case of bioethanol is expressed by using the Formula 3.7 and 3.8:

$$\Delta C_f = (B_{fdT1} c_{fd}) - (B_{fdT2...T5} c_{fd} + B_{fetT2...T5} c_{fetpT2...T5}), \qquad 4.1$$

where $c_{fetpT2...T5}$ – LGBE production prices according to ethanol content.

Thus the relative cost of fuel consumption does not decrease by 30%, but is expressed with the following formula:

$$\Delta C_f \% = \frac{100 \Delta C_f}{C_{fd}}, \quad 4.2$$

This results in 14.4% relative decrease in the fuel cost when using 60% LGBE as opposed to using 90% LGBE, which is directly associated with the expenses on machinery (Persitski, 2006). Use of relative values allows comparison of bioethanol use in the vehicles with different types of internal combustion engines.

4.6. The calculation of measuring system's measurement uncertainty for using diesel fuel

Results of the measurements:
The measurement results concerning diesel fuel have been given in the following Table 4.1.

Table 4.1. Measurement results (3 tests) using diesel fuel

Test	α_{pd}, rotations	n_e, min^{-1}	T_e,Nm	B_{fdk}, kg h^{-1}
1	0-closed	1800	90	4.9
2	0-closed	1800	90	4.8
3	0-closed	1800	90	4.8

T_e, N·m – torque and its uncertainty on the basis of test bench data. Max accuracy, torque ± 0,1 % related to full scale M_{max}, which in the case of test conditions was:

$$M_{\max} = \frac{650 \cdot 0.1}{100} = 0.65\%$$

System deviation, torque ± 0.17 related to full scale SD_{max}:

$$SD_{\max} = \frac{650 \cdot 0.17}{100} = 1.105\%$$

n_e, min^{-1} – system deviation, speed 0,25 ‰ related to full scale n_{max}, for frequency content smaller than 1Hz. This value is very small in per cents, therefore it can be disregarded.

$B_{fdk.avg}$ – average hourly diesel fuel consumption, kg h^{-1}. This value can be characterised by both type A and B measurement uncertainty.

Therefore the average hourly fuel consumption of three tests was calculated:

$$B_{fdk.avg} = (4.9 + 4.8 + 4.8)/3 = 4.83 \text{ kg h}^{-1}$$

The type A standard uncertainty of this can be calculated using the following formula 3.17:

$$U_A = \sqrt{\frac{1}{3(3-1)} \sum (4.9 - 4.83)^2 + (4.8 - 4.83)^2 + (4.8 - 4.83)^2} =$$

$$= 0.033 \text{ kg h}^{-1}$$

Type B uncertainty is conventional—½ from the last point of measurement and for this test instrument it was 0.05. In changing to standard uncertainty, the type B uncertainty is achieved with the following formula 3.19:

$$U_B = \frac{0.05}{\sqrt{3}} = 0.029 \text{ kg h}^{-1}$$

The type B uncertainties caused by human factors (measuring time with the stopwatch) can be disregarded as the time spent on turning the stopwatch on and off, which is a total of ca 1 second, can be included in the fuel consumption uncertainty. Generally, the measurements are performed automatically at a rate of 60 times a minute.

As the next step, the cumulative standard uncertainty *U* of the measuring system will be calculated using the formula 3.16:

$$U = \sqrt{0.033^2 + 0.029^2} \cong 0.044 \text{ kg h}^{-1}$$

The measurement extended uncertainty is the measurement standard uncertainty multiplied by two:

$$U_e = 0.044 \cdot 2 = 0.088 \text{ kg h}^{-1},$$

which in the case of a normal distribution coverage factor $k_U = 2$ is equal to 95% probability.

In case of normal distribution coverage factor k_U=2 we can say with 95% probability that our rated fuel consumption's mean measurement uncertainty is within the limits 0.088 kg h^{-1} or ±88 g h^{-1}.

CONCLUSIONS

It can be claimed about the use of bioethanol produced on the basis of lignocellulose raw material under Estonian conditions that:

1. The amount of fuel produced from one hectare of natural grasslands is seven times lower than using other crops (grain, maize, etc.). The production technology must be improved and Estonian University of Life Sciences will work in this direction.
2. All of the raw materials must be utilised in the production of bioethanol, for example, by converting production residues to biogas.
3. The production and use is rational for agricultural companies due to the amounts of raw material and location and bioethanol yield, which is quite limited.
4. Lignocellulose bioethanol can be used to cover up to 10% of the need for diesel fuel in agriculture, <u>if only green biomass is used as the raw material</u>. The biogas produced from production residues can be used in stationary equipment (heating furnaces and generators).
5. Depending on the chemical and physical properties of bioethanol, it is reasonable to use an additional fuel supply system (device), the prototype of which has been developed within this thesis (Patent Application: P201100021). The pre-tests have been performed and the device is being developed further. The need for an additional fuel supply system was indicated by the durability tests which revealed fuel supply system wear.
6. While using lower concentration bioethanol (70% by volume) the residues do not have significant influence on the engine power and economic parameters.
7. The use of 60% bioethanol resulted in the relative cost of fuel reducing by 14.4% in comparison with the use of 90% bioethanol. When using bioethanol with 90% concentration, the engine needs 21% of the total consumed fuel to be diesel fuel; at the same time 60% bioethanol requires 36% diesel fuel.
8. Special engine tests must be run with a specific engine being studied to evaluate the use of bioethanol in internal combustion engines. The graphs presented in this thesis cannot be used for evaluating engines with different designs. Universal additional fuel supply device must be developed and an engine specific fuel portfolio must be prepared. The engine testing laboratory

of Estonian University of Life Sciences has all the necessary measuring equipment for performing tests.

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KOKKUVÕTE

Kirjanduse (BP Statistical Review of World Energy June 2011) põhjal on bioetanooli tootmise kasv kõige suurem Põhja-, Lõuna- ja Kesk-Ameerikas. Ameerika mandri biokütuste tootmine moodustas kolm neljandiku kogu maailmas toodetavast biokütusest. Euroopas moodustas bioetanooli toodang 21,1% kogu biokütuste mahust 2010 aastal. Enamasti toodetakse bioetanooli toiduainetega konkureerivast toorainest (ILUC 2012), mida võib liigitada esimese põlvkonna tootmistehnoloogiate hulka. Eestis puudub bioetanooli tootmine sisepõlemismootori kütusena. Uurimuse käigus teostatud analüüsi põhjal on rohtsest biomassist saadava bioetanooliga Eestis võimalik katta ca 10% kulutatavast diislikütuse kogusest põllumajanduses. Selliselt biokütust kasutades on võimalik täita direktiivi 2009/28/EÜ nõudeid. Bioetanooli hinda mõjutab tugevalt tooraine ja tehnoloogia valik. Kui kasutada tooraineks lignotselluloosset materjali (teise põlvkonna tootmistehnoloogiad), siis tootmisele tehtavad kulutused mõnevõrra suurenevad. Põhjuseks on eeltöötlusele tehtavate kulutuste suurenemine protsessis kasutatavate kemikaalide kõrge maksumuse tõttu. Kirjanduse (BioScopes, 2006; Etek Etanolteknik AB, 2010; Demirbas, 2009) põhjal on enamasti uuritud veevaba ja vähest vett sisaldavat etanooli (vee sisaldus 2%) kasutamist mootorikütusena. Madala kontsentratsiooniline bioetanool (talu etanool), mis sisaldab jääkaineid ei ole laialdast kasutamist ja uurimist leidnud. Madala kvalitaadilise bioetanooli tootmisel on võimalik kasutada lihtsamat tootmismeetodit, mis vähendab kulutusi tootmisele ja laiendab tootjate arvu. Lignotselluloossel toorainel põhineva etanooli tootmise märgatavat kasvu kinnitavad ka tuleviku prognoosid (IEA 2008).

Doktoritöö eesmärgiks oli uurida madala kontsentratsioonilise bioetanooli kasutamise võimalusi sisepõlemismootori kütusena väikese ja keskmise suurusega põllumajandusettevõtetes. Sellest tulenevalt oli üheks alleesmärgiks leida minimaalne etanoolsegu kontsentratsioon, millega mootor töötab rahuldavalt testplaani ülekoormuspiirkonnas. Analüüsida uuritava kütusesegu võimalikke kasutusviise ja nende mõju diiselmootori põlemisprotsessile. Küttesegu koostise hindamisel kasutati kvalitatiivseid ja kvantitatiivseid segumoodustusviise. Kütusekomponentide kvantitatiivne vahekord ja nende kasutusvõimalused diiselmootoris määratakse kindlaks erinevate segumoodustusviiside optimeerimise teel. Pakuti välja kohalik alternatiivkütuse koostis ja hinnati selle kasutusmeetodit mootormeetodil. Alternatiivkütuse füüsikalis-keemilisi omadusi hinnati mootori põlemisprotsessi indikaatornäitarvude ja mootori väljundparameetrite mõõtmise teel. Töös on esitatud tehnilised soovitused kohaliku alternatiivkütuse koostamiseks ja selle kasutamiseks diiselmootoris.

Doktoritöö tulemused on kokkuvõetult järgmised.

1. Jääkainete mõju bioetanooli kasutamisel. Madalama kvaliteediliste etanoolkütuste kasutamisel jääkainete sisaldus ei avalda määravat mõju mootori väljundparameetritele. Eelkatsetusi valitud mootori ökonoomsuslike ja võimsuslike parameetrite hindamiseks võib teostada destilleeritud veega lahjendatud etanooli kasutades imiteerimaks nn alternatiivset etanooli. Kvaliteetse etanooli lahjendatud segude kasutamine mootorkatsetel vähendab tunduvalt kulutusi. Samas heitgaaside sisalduse määramisel ja hindamisel tuleb teostada katsed alternatiivse etanooliga, mida kavatsetakse mootoris kasutada. Edasistes uurimustes heitgaaside osas on tarvis teostada täiendavaid uurimusi madalma kontsentratsiooniga etanooli kasutamisel, kuna ei ole teada jääkainete mõju heitgaasidele ja keskkonnale.

2. Tulemused survesüütega mootoris D-120 erineva kvaliteediklassiga etanoolkütuse kasutamisel on järgmised:
   1) mootor töötab rahuldavalt 96 % etanool lisandkütusega kuni tunnikuluni $B_{f.et} = 4{,}8 \text{ kg h}^{-1}$;
   2) 96 % etanoolkütuse kasutamise korral võib diisli- ja etanoolkütuse vahekord kasvada suhteni 1:4;
   3) mida suurem on etanoolkütuse kontsentratsioon, seda suurem on mootori efektiivkasutegur;
   4) etanoolkütuse lisamisel väheneb mootori efektiivkasutegur lineaarselt;
   5) mootor töötab maksimaalsel koormusrežiimil suuremate pilootpritse koguste korral 60 % etanool lisandkütusega rahuldavalt kuni 4,5 kg h^{-1};
   6) 60 % etanoolkütuse kasutamise korral on mootori efektiivkasutegur ca 10 % väiksem, kui 96 %-lise etanoolkütuse korral.

3. Katsetes diiselmootori kõrgsurvepumba UTN 5A väljundparameetritele ja toiteaparatuuri alasüsteemide detailidele selgus, et:

1) pumba sektsioonide tootlus etanooli korral ei muutu oluliselt samade toiteaparatuuri tööparameetrite juures, võrreldes diislikütuse kasutamisega;
2) etanooliga töötamisel ei ilmnenud olulisi tööpindade kahjustusi, mis võiksid mõjutada toiteaparatuuri tootlust ja töökindlust;
3) mõõdetud töödetailide geomeetriline ümarus üldjuhul paranes. Sellest saab järeldada, et etanooli keskkond sobib uurimuses käsitletud detailide sissetöötamiseks;
4) madala viskoossuse tõttu, antud tüüpi kõrgsurvepumba kasutamisel, satub etanool läbi plunžripaaride määrdeõli hulka;
5) etanooliga töötanud toiteaparatuuris, mis on pikemaks ajaks seisma jäänud, on tööpindade korrodeerumise oht suurem kui diislikütusega töötanud aparatuuri puhul.

4. Doktoritöö käigus töötati välja kolbmootori küttesegu moodustamise meetod ja põimtoitesüsteem (patent EE 05665 B1) ja sellele vastava SPM-i lisatoitesüsteemi esialgne prototüüp. Eesmärk süsteemi arendamisel on kasutada erinevate omadustega vedelaid biokütuseid sisepõlemismootoris. Lisatoitesüsteem on sobiv, kui soovime kasutada bioetanooli olemasolevas masinapargis. Sellisel juhul jääb ära probleem mootori käivitamisel madalatel temperatuuridel, mis on tingitud etanooli omadustest. Samuti ei pea muretsema bioetanooli madalama määrimisvõime ja suurema korrosiooni mõjust toiteaparatuurile võrreldes diislikütusega.

5. Bioetanoolkütuse hind kujuneb sõltuvalt kontsentratsioonist ja on leitav arvutusliku mudeliga. Mudel võimaldab hinnata, milliseks kujuneb bioetanoolkütuse suurim piirhind võrreldes tavakütuse hinnaga tingimusel, et kulutatud bioetanoolkütuse maksumus C_{fbio} oleks väiksem tavakütuse maksumusest C_{freg} sama töö tegemisel. Lisaks on võimalik hinnata kuidas muutuvad vajalikud kütuste kogused, kui võetakse kasutusele bioetanoolkütus kas täielikult või osaliselt. Etanooli kontsentratsiooni muutudes on hinna vahe Δc_f, muutuv. Kui madalama kontsentratsioonilise bioetanooli (60 %) kasutamise piirhind langeb võrreldes kõrgema kontsentratsioonilise bioetanooli (90 %) kasutamisega 28,4 %, siis tootmishinna

langus 50 %-ga on tunduvalt suurem. Seega võib väita, et madalama kontsentratsioonilise bioetanooli tootmine uuritavatel tingimustel on mõistlik. Samas tuleb arvestada, et kasutades madalama kontsentratsioonilist bioetanooli vajab survesüütega mootor suuremat diislikütuse kogust. Kasutades 90 %-list bioetanooli vajab mootor 21 % diislikütust kogu tarbitud kütuse kogusest, samas kasutades 60 %-list bioetanool vajab mootor 36 % diislikütust.

6. Töö tulemusena võib öelda, et sõltuvalt bioetanooli omadustest, kohaliku masinpargi koosseisust ja keskkonna tingimustest on bioetanooli laialdane kasutamine mootorikütusena Eestis esialgu probleemne, kuid edaspidi reaalne.
   Toorainest lähtuvalt on mõistlik kasutada bioetanooli osana kütusesegust. Põllumajanduses on olemas piisav tooraine ressurss, kui soovitakse kasutada toorainena lignotselluloosset biomassi. Bioetanooli tootmine lignotselluloossest biomassist on mõistlik juhul, kui tootmisjääk väärindatakse biogaasiks. Uuringute tulemusel selgus, et bioetanooli ja biogaasi koostootmisel 11,5 % madalama tulemuse toodetava energia võrdluses, kui toota ainult biometaani. See ei ole halb tulemus võrreldes kirjanduse (FRN, 2011) põhjal saadud andmeid, kus on erinevus ca 47 % ning selge eelis on biometaani tootmisel (kasutades maisi ja teravilja).
   Masinpargi seisukohalt on samuti mõtekas bioetanooli kasutada osana tarbitavas kütuses, kuna kulutused masinpargile on lisatoitesüsteemi kasutades tunduvalt väiksemad, kui olemasolevate mootorite asendamisel etanooli mootoritega. Kasutades põllumajanduses survesüütega mootoreid, tuleb teostada ümberseadistus ja paigaldada lisatoiteseadmed. Lisatoiteseadmete paigaldamise eelis võrreldes mootori ümberehitamisega on vähem kulukas. Samuti säilib võimalus kasutada ainult põhitoitesüsteemi, kui biokütuse kasutamine osutub probleemseks kasutajast sõltumata (tooraine hinna või maksu muutused). Kasutades lisatoiteseadmeid jääb ära probleem diislikütuse segamisel etanooliga (üle 20%). Puuduseks on lisa (bio-) kütuse mahutile koha leidmine, kuid see probleem on tehniline ja seega lahendatav.
   SPM väljundparameetrite hindamisel on saadud paremaid tulemusi kasutades lisa toiteseadmeid, kus kütuse etteandeks kasutatakse nn fumigeerimismeetodit. Lisa toiteseadmete

kasutamisel võrreldes biokütusesegu kasutamisel survesüütega mootoris vähenevad heitgaaside näitajad CO, HC ja tahmasuse osas ning suureneb termiline kasutegur.
Seega on oluline arendada välja ja evitada universaalne lisatoitesüsteem. See arendustöö ei kuulunud andtud doktoritöö hulka, kuid andis tõuke sellealase tegevuse alustamiseks Eesti Maaülikooli tehnikainstituudi sisepõlemismootorite katselaboris.

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CURRICULUM VITAE

Personal data

Name:	Arne Küüt
Date of birth:	16. Juuli 1968
Address:	Estonian University of Life Sciences, Kreutzwaldi 56, Tartu
Phone:	+372 522 9181
E-mail:	arne.kyyt@emu.ee
Family:	Married, 2 children

Education:

2008...	PhD studies , Estonian University of Life Sciences, Institute of Tehnology
2006 – 2008	Master's degree studies , Estonian University of Life Sciences, Institute of Tehnology
2001 – 2006	Tallinn, College of Engineering
1983 – 1987	Luua Forestry School
1975 – 1983	Tartu Secondary School

Research activity

Degree information:

2008	M.Sc.Agr.Eng.degree (Estonian University of Life Sciences, Institute of Tehnology)

Honours and awards:

2010	Invention contest of Institute of Technology and College of Technology "Engineering Student Invents 2010" I place. "More Power System bioethanol for use in diesel engines"

Field of research:

Natural Sciences and Engineering, Energetic Research

Complement education:

2007	The planning and implementation of EU structural funds in Estonia, Ministry of Finance
2008	Computational methods of systems biology, Latvia University of Agriculture, BOVA course, Jelgava.
2008	Safety adviser training in carriage of dangerous goods, College of Engineering
2009	TC5 "`Biogas, Energy supply", RWTH Aachen University, Linz-Austria , The WISE project is funded by Marie Curie Program – EC (Contract number: MSCF-CT-2006-045669).

2009	"Self-expression art foundations." Trainer Ingo Normet, Estonian Music and Theatre Academy. Estonian University of Life Sciences of the Open University course training.
2010	"The company and / or product presentation material development". Presentation map portfolio: materials, opportunities, observation and analysis. Tartu Art School.
2010	Teamwork training "Public Speaking." Katrin Aedma ITF (International Training Fellow), Travel In Private School Trainings.
2011	"Requirements for all-terrain vehicles and assigning roadworthiness" and "Didactics". Estonian Entrepreneurship University of Mainor.
2012	"Traffic Planning and Management". MoMa.BIZ project, Tartu.
2012	"T-category tractor teacher training." Estonian Entrepreneurship University of Mainor.

Current projects:

2012	Project 8-2/T12146TEPT Addinol MZ 408 two-stroke engine oil extensive usage. Principal investigator (responsible person: Jüri Olt)

Dissertations supervised:

2011	Omari Otsa, Master's degree, (sup) **Arne Küüt**, Pulveriser blending system of liquid biofuels.
2011	Rivo Sepping, Master's degree, (sup) **Arne Küüt**, Performance characteristics of the pulveriser device.
2013	Vello Lääts, Master's degree, (sup) **Arne Küüt**, Risto Ilves, Endurance test bench of feeding system of diesel engine.

Career:

2008...	PhD studies , Estonian University of Life Sciences, Institute of Tehnology
1992 - 1996	Autokoolitus AS, master of training
1996...	Autokoolitus OÜ, manager

ELULOOKIRJELDUS

Isiku andmed

Nimi:	Arne Küüt
Sünniaeg:	16. Juuli 1968
Aadress:	Eesti Maaülikool, Kreutzwaldi 56, Tartu
Telefon:	+372 522 9181
E-post:	arne.kyyt@emu.ee
Perekond:	Abielus, 2 last

Haridustee

2008...	Eesti Maaülikool, tehnikainstituut, doktorant
2006 – 2008	Eesti Maaülikool, tehnikainstituut, magister
2001 – 2006	Tallinna Tehnikakõrgkool, bakalaureus
1983 – 1987	Luua Kõrgem Metsanduskool (Kaarepere Põllumajandustehnikum)
1975 – 1983	Tartu 2. Keskkool

Teadustegevus

Teaduskraadi info:

2008	Tehnikateaduste magister põllumajandustehnika erialal (Eesti Maaülikool)

Teaduspreemiad ja-tunnustused:

2010	EMÜ Tehnikainstituudi ja Tartu Tehnikakolledži leiutuskonkurss "Tehnikatudeng leiutab 2010", I koht. "Lisatoitesüsteem bioetanooli kasutamiseks diiselmootorites"

Teadustöö põhisuunad:

Loodusteadused ja tehnika, Energeetikaalased uuringud.

Täiendkoolitus:

2007	Euroopa Liidu struktuurivahendite planeerimine ja rakendamine Eestis, Rahandusministeerium.
2008	Computational methods of systems biology, Latvia University of Agriculture, BOVA course, Jelgava.
2008	Ohtlike veoste veo ohutusnõuniku väljaõpe, Tallinna Tehnikakõrgkool.
2009	TC5 "`Biogas, Energy supply", RWTH Aachen University, Linz-Austria , The WISE project is funded by Marie Curie Program – EC (Contract number: MSCF-CT-2006-045669).
2009	"Eneseväljenduskunsti alused". Koolitaja Ingo Normet, Eesti Muusika- ja Teatriakadeemia lavakunstikkoli juhataja. Eesti Maaülikooli avatud ülikooli täiendõppekursus.
2010	"Ettevõtte ja/või toote esitlusmaterjalide kujundamine". Tartu Kunstikool.

2010	Meeskonnatöö koolitus "Avalik esinemine". Kooliaja Katrin Aedma ITF (International Training Fellow), Erakool Travel iN Trainings.
2011	"Nõuded mootorsõiduki tehnoseisundile ja tehnoseisundi määramine" ja "Didaktika". Eesti Ettevõtluskõrgkool Mainor.
2012	"Liikluse planeerimine ja juhtimine". Projekt MoMa.BIZ, Tartu Linnavalitsus.
2012	"T- kategooria traktori ja liikurmasinajuhi õpetaja koolitus". Eesti Ettevõtluskõrgkool Mainor.

Jooksvad projektid:

2012	Projekt 8-2/T12146TEPT Addinoli kahetaktilise mootoriõli MZ 408 kasutusvõimaluste laiendamine. Põhitäitja (Vastutav täitja: Jüri Olt)

Juhendatud väitekirjad:

2011	Omari Otsa, magistrikraad, (juh) **Arne Küüt**, Vedelate biokütuste pulverisaatorsegamisseade.
2011	Rivo Sepping, magistrikraad, (juh) **Arne Küüt**, Pulverisaatorseadme tööparameetrite karakteristikud
2013	Vello Lääts, magistrikraad, (juh) **Arne Küüt**, Risto Ilves, Diiseltoiteaparatuuride kestvuskatse stend.

Teenistuskäik:

2008...	Eesti Maaülikool, tehnikainstituut, doktorant
1992 - 1996	Autokoolitus AS, väljaõppe meister
1996...	Autokoolitus OÜ, juhatuse liige

ETTEKANDED

Suulised ettekanded rahvusvahelistel konverentsidel:

- ENGINEERING FOR RURAL DEVELOPMENT, Mai 28 – 29, 2009, Jelgava, „PRODUCTION OF VEGETABLE OIL AS FUEL“ **Küüt, A**., Olt, J.;
- ENERGY EFFICIENCY AND AGRYCULTURAL ENGINEERING , Oktober 01 – 03, 2009, Rousse, „MIXTURES OF BIOETHANOL AND GASOLINE AS OTTO MOTOR FUEL“Olt, J.; Mikita, V., Sõõro, T., **Küüt, A**., Tamm, R., Raidla, E., Ristlaid, K.;
- ACTUAL TASKS ON AGRYCULTURAL ENGINEERING, February 22 – 26, 2010, Opatija, „USE OF BIOETHANOL FUEL AS REGULAR FUEL“ **Küüt, A**., Olt, J.;
- BIOSYSTEMS ENGINEERING, May 13 – 14, 2010, Tartu, “STATE OF THE ART IN BIOETHANOL PRODUCTION”*,* Ristlaid, K., **Küüt, A**., Olt, J.;
- BIOSYSTEMS ENGINEERING, May 12 – 13, 2011, Tartu, “ STUDY OF POTENTIAL USES FOR FARMSTEAD ETHANOL AS MOTOR FUEL” *,* **Küüt, A**., Ristlaid, K., Olt, J.;
- 40 rahvusvaheline konverents, ACTUAL TASKS ON AGRYCULTURAL ENGINEERING, February 21 – 24, 2012, Opatija, „The characteristics of bioethanol fuel in internel combustion engines with compression-ignition“ **Küüt, A**., Ilves, R., Mikita, V., Olt, J.;
- ENGINEERING FOR RURAL DEVELOPMENT, Mai 24 – 25, 2012, Jelgava, „Cost of ethanol when used in diesel engine“ **Küüt, A**., Ilves, R., Olt, J.;
- BIOSYSTEMS ENGINEERING, May 10 – 11, 2012, Tartu, “ Characteristics describing the price formation of bioethanol used as the fuel for an internal combustion engine.”*,* **Küüt, A**., Panova, O., Olt, J.
- BIOSYSTEMS ENGINEERING, May 9 – 10, 2013, Tartu, “ Characteristics of bioethanol fuel obtained from lignocellulose biomass internal combustion reciprocating engines with spark- and compression-ignition.”*,* **Küüt, A**.,

Stendi ettekanne rahvusvahelisel konverentsil:

- BIOSYSTEM ENGINEERING, May 13 – 14, 2010, Tartu, “SPECIFIC FEATURES OF ESTABLISHMENT AND MAINTENANCE OF TRACTOR FLEET IN A TYPICAL ESTONIAN AGRICULTURAL HOLDING” , Traat, Ü., **Küüt, A**., Olt, J.

Suulised ettekanded kohalikel konverentsidel:
- „XLI Teaduslik-praktiline konverents PÕLLUNDUS- JA FARMITEHNIKA 2009“ 20. novembril 2009.a. Tartus , “BIOENERGEETIKAALASED ARENDUSED TEHNIKAINSTITUUDIS ” 2009, **Arne Küüt**.

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- "Taastuvate energiaallikate uurimine ja kasutamine X (TEUK X)" 13. novembril 2008.a. Tartus, „TAIMEÕLI TOOTMINE JA KASUTAMINE MOOTORIKÜTUSENA“, **Arne Küüt**, Jüri Olt,;
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VIIS VIIMAST KAITSMIST

MIGUEL PORTILLO ESTRADA

ON THE RELATIONSHIPS BETWEEN PLANT LITTER AND THE CARBON AND NITROGEN CYCLES IN EUROPEAN FOREST ECOSYSTEMS
EUROOPA METSAÖKOSÜSTEEMIDE SÜSINIKU- JA LÄMMASTIKURINGE SEOSED TAIMSE VARISEGA
Prof. **Ülo Niinemets**, teadur **Steffen Manfred Noe**
30. mai 2013

ZHIHONG SUN

ISOPRENE EMISSION FROM ASPEN (*Populus sp.*) IN RELATION TO ENVIRONMENTAL DRIVERS
KESKKONNATEGURITE MÕJU HAAVA (*Populus sp.*) ISOPREENI EMISSIOONILE
Prof. **Ülo Niinemets**
5. juuni 2013

MIRJAM VALLAS

GENETIC AND MODELLING ASPECTS OF MILK COAGULATION PROPERTIES IN DAIRY CATTLE
PIIMA LAAPUMISOMADUSTE MODELLEERIMINE JA GENEETILINE DETERMINEERITUS
Vanemteadur **Elli Pärna**, dots. **Tanel Kaart**, prof. **Kalev Pärna** (Tartu Ülikool)
27. juuni 2013

KARIN KALJUND

GENETIC DIVERSITY, GENOTYPIC STRUCTURE AND VULNERABILITY OF NATIVE POPULATIONS OF SICKLE MEDIC (*MEDICAGO SATIVA* SSP. *FALCATA*) IN ESTONIA
SIRPLUTSERNI (*MEDICAGO SATIVA* SSP. *FALCATA*) LOODUSLIKE POPULATSIOONIDE GENEETILINE MITMEKESISUS, GENOTÜÜPNE STRUKTUUR JA OHUSTATUS EESTIS
Vanemteadur **Malle Leht**, vanemteadur **Vello Jaaska**
27. august 2013

LIINA ARUS

THE INFLUENCE OF CULTIVAR AND NATURAL ENEMIES ON RASPBERRY BEETLE (*Byturus tomentosus* De Geer)
SORDI JA LOODUSLIKE VAENLASTE MÕJU VAARIKAMARDIKALE (*Byturus tomentosus* De Geer)
Prof. *emer.* **Anne Luik**
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